Energy-Efficiency Improvement Potential of Multi-split Air Conditioning Systems in China

Authors:

Nihan Karali, Chao Ding, Won Young Park, Nihar Shah, and Jiang Lin

Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory
International Energy Analysis Department

April 2020

This work was supported by the Kigali Cooling Efficiency Program through Energy Foundation China under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy.

DISCLAIMER

COPYRIGHT NOTICE

Energy-Efficiency Improvement Potential of Multi-split Air Conditioning Systems in China

Nihan Karali, Chao Ding, Won Young Park, Nihar Shah, and Jiang Lin

Abstract

In 2015, the market for variable refrigerant flow (VRF) air conditioning systems in China totaled 3.7 billion U.S. dollars, representing 13% of the total packaged air conditioning market, and the VRF market share has grown rapidly. This report provides context for assessing China's minimum energy performance standard (MEPS) for VRF systems by analyzing the costs and benefits of efficiency improvements via various technological advancements. Currently, the best available VRF systems in Japan currently achieve Japanese annual performance factor (APF) 6.5–6.6 (China APF of roughly 5.0-5.5, based on our preliminary estimates). In general, the best available VRF systems available in major economies surpass the highest efficiency levels recognized by labeling programs by at least 20%. In addition, there are multiple VRF systems manufactured in China that have system EER ratings of 4.00 and higher. Some Chinese manufacturers also reported a China APF range of 4.60-5.00 for the VRF systems with an integrated part load value (IPLV) range of 6.05-6.60. In this analysis, we model four representative VRF systems—with cooling capacities of 14 kilo-watts (kW), 18 kW, 40 kW , and 85 kW—based on the Chinese market's most common configurations and using China-specific component data and product specifications from manufacturer literature and industry experts. For each VRF system type, we evaluate 144 different design combinations of efficient technologies and estimate the least-cost combinations able to reach target efficiency levels, relying heavily on recent literature and input from industry experts in the Chinese market. We analyze consumer impacts by calculating net lifetime savings and payback period for each level of efficiency improvement. The results show that China has great opportunity to improve its VRF system efficiency using cost-effective technologies. With stringent MEPS levels, sufficient incentives, and robust regulatory programs such as labeling and procurement programs, high-efficiency VRF systems can be developed and deployed in China.

Contents

Table of Figures

Table of Tables

Acronym List

AC	air conditioner
AHRI	Air-conditioning, Heating and Refrigeration Institute
APF	annual performance factor
BAT	best available technology
CC	cooling capacity
COP	coefficient of performance
CVT	controls verification test
DC	direct current
DOE	U.S. Department of Energy
EER	energy efficiency ratio
EU	European Union
FSD	fixed-speed drive
HDD	heating degree day
HE	heat exchanger
HP	heat pump
HSPF	heating seasonal performance factor
IEER	integrated energy efficiency ratio
IPLV	integrated part load value
MEPS	minimum energy performance standard
PAC	packaged air conditioner
PLF	part load factor
PTAC	packaged terminal air conditioner
RAC	room air conditioner
SEER	seasonal energy efficiency ratio
U.S.	United States
VRF	variable refrigerant flow
VSD	variable-speed drive

Executive Summary

In 2015, the market for variable refrigerant flow (VRF) air conditioning systems in China totaled 3.7 billion U.S. dollars, representing 13% of the total packaged air conditioning market, and the VRF market share has grown rapidly. This report provides context for assessing China's minimum energy performance standard (MEPS) for VRF systems by analyzing the costs and benefits of efficiency improvements via various technological advancements. We model four representative VRF systems—with cooling capacities of 14 kW (residential - representing cooling capacity (CC) ≤ 14 kW category), 18 kW (residential - representing 14 kW < CC ≤ 28 kW category), 40 kW (commercial - representing 28 kW < CC ≤ 68 kW category), and 85 kW (commercial - representing 68 kW < CC category)—based on the Chinese market's most common configurations and using China-specific component data and product specifications from manufacturer literature and industry experts. For each VRF system type, we evaluate 144 different design combinations of efficient technologies and estimate the least-cost combinations able to reach target efficiency levels, relying heavily on recent literature and input from industry experts in the Chinese market. We analyze consumer impacts by calculating net lifetime savings and payback period for each level of efficiency improvement.

The results show that China has great opportunity to improve its VRF system efficiency using cost-effective technologies. With stringent MEPS levels, sufficient incentives, and robust regulatory programs such as labeling and procurement programs, high-efficiency VRF systems can be developed and deployed in China.

The following are key findings and implications of this study:

- The best available VRF systems in Japan currently achieve Japanese APF 6.5–6.6 (China APF of roughly 5.0-5.5, based on our preliminary estimates). In general, the best available VRF systems available in major economies surpass the highest efficiency levels recognized by labeling programs by at least 20%.
- There are multiple VRF systems manufactured in China that have system EER ratings of 4.00 and higher. In addition, some Chinese manufacturers reported a China APF range of 4.60-5.00 for VRF systems with an IPLV range of 6.05-6.60.
- Increasing the efficiency of small-capacity VRF systems (considered CC ≤ 28 kW in this report)) to APF 5.5—representing about 30% efficiency improvement, which are common for residential use—is feasible and beneficial. There are already multiple models from Chinese manufacturers reported to have APF rating ranging from 4.6 to 5.0, an APF 5.5—the highest efficiency in the Japanese market for these categories
    - could be achieved at a price increase of about 12%, compared with the price of a baseline APF 4.2 VRF system.
    - likely would provide large consumer benefits in the form of net savings over a system's lifetime; the payback period varies little between efficiency levels of APF 5.0 and 5.5, and is less than 5 years in most of the cases.
- Increasing the efficiency of large-capacity VRF systems (common for commercial use) to APF 5.5 for systems is also feasible and beneficial.
    - It could be achieved at a price increase of about 10%, compared with the price of a baseline APF 4.2 VRF system.
    - It likely would provide large benefits to commercial customers in the form of net savings over a system's lifetime, and it could pay back faster than residential units do because of longer hours of use.

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems provide a variety of services such as heating, cooling, ventilation, and humidity control. There is a wide range of HVAC systems available, including the basic window-fitted units, mini-split systems, multi-split systems - featuring variable refrigerant flow (VRF) as well -, medium and large-scale package units, and so on. In its large packaged air conditioner (PAC) report, BSRIA (2016) notes that VRF is the second biggest market by value among all types of PAC products in China, even though its share by volume is small (Figure 1). The figure shows that almost hundred percent of multi-split units in China (shown as Multi splits and VRF in Figure 1) is VRF systems.

VRF systems were originally developed in Japan in 1982 (Thornton and Wagner, 2012). They entered the HVAC market in China in the late 1990s, but market penetration was minimal. Between 2015 and 2017, however, VRF sales in China grew at a compound annual growth rate of more than 20% (Khanna et al., 2019). In 2015, the Chinese VRF market totaled 3.7 billion U.S. dollars, representing 13% of the total PAC market (BSRIA, 2016).

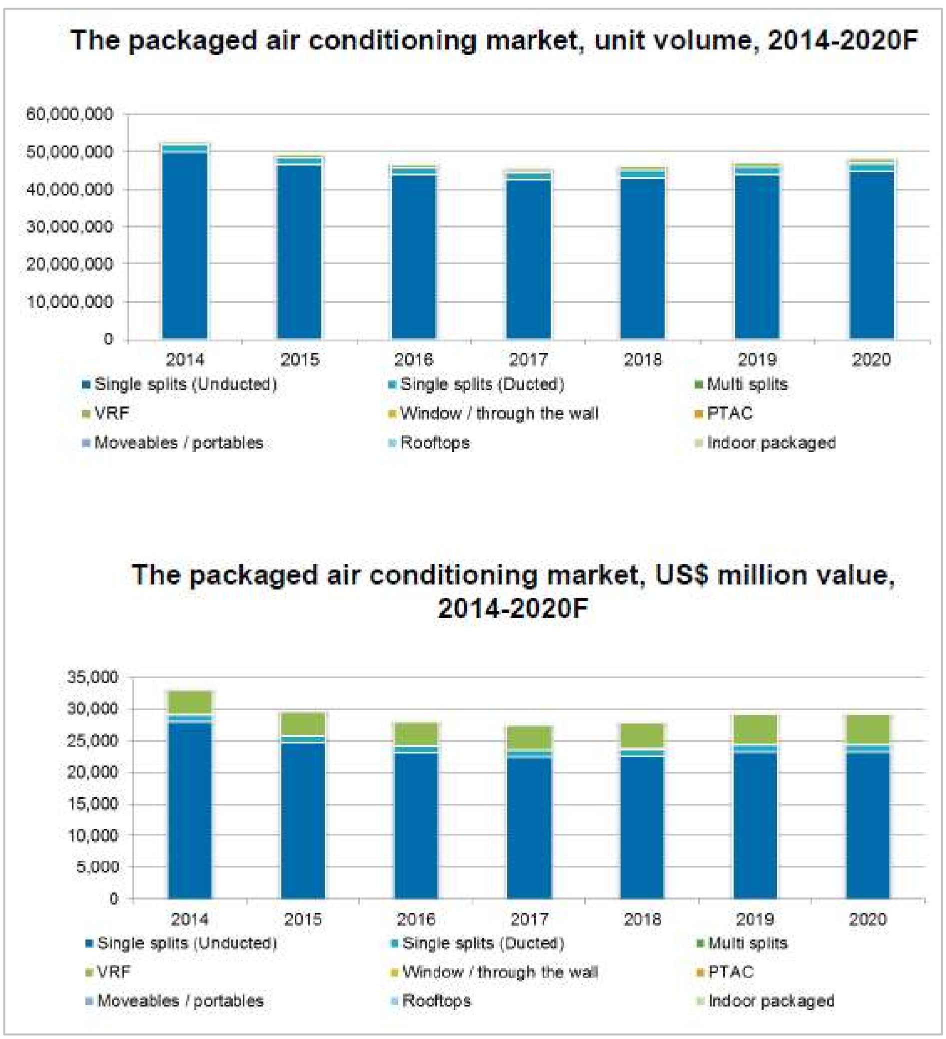


Figure 1. China's historical and forecasted (F) PAC market by product type, 2014–2020
Note: Please see Appendix A1 for the definitions of key product groups.
Source: BSRIA (2016)

To date, VRF systems in China are not covered by a dedicated minimum energy performance standard (MEPS). Instead, they are included under the China MEPS issued for multi-split systems in 2008, based on the integrated part load value (IPLV) efficiency index (Table 1). However, as Figure 2 shows, the model-weighted average IPLV for multi-split ACs in 2016 was 2.6–3 times higher than the current MEPS, and the efficiency of this market segment increased 50%–65% between 2012 and 2016. Clearly, China's current multi-split MEPS is outdated.

In addition, current Chinese MEPS for multi-split ACs does not consider any climate zone difference. In contrast, single-phase VRF multi-split systems smaller than 19 kW (65,000 Btu/h) are covered in the U.S. residential central ACs/heat pumps (HPs) MEPS, which divides the country into three climate zones and applies different efficiency levels. No such division exists for VRF systems larger than 19 kW. See the Appendix A2 and A3 for details of the U.S. MEPS.

Table 1. China's Energy-Efficiency Label Grade Thresholds for Multi-Split Air Conditioning (AC) Systems

Nominal Cooling Capacity (CC) [kW]	IPLV (Cooling) Level [W/W]				
	Grade 5 (MEPS)	Grade 4	Grade 3	Grade 2	Grade 1
CC ≤ 28	2.80	3.00	3.20	3.40	3.60
28 < CC ≤ 84	2.75	2.95	3.15	3.35	3.55
CC > 84	2.70	2.90	3.10	3.30	3.50

Source: GB 21454-2008 (2008)

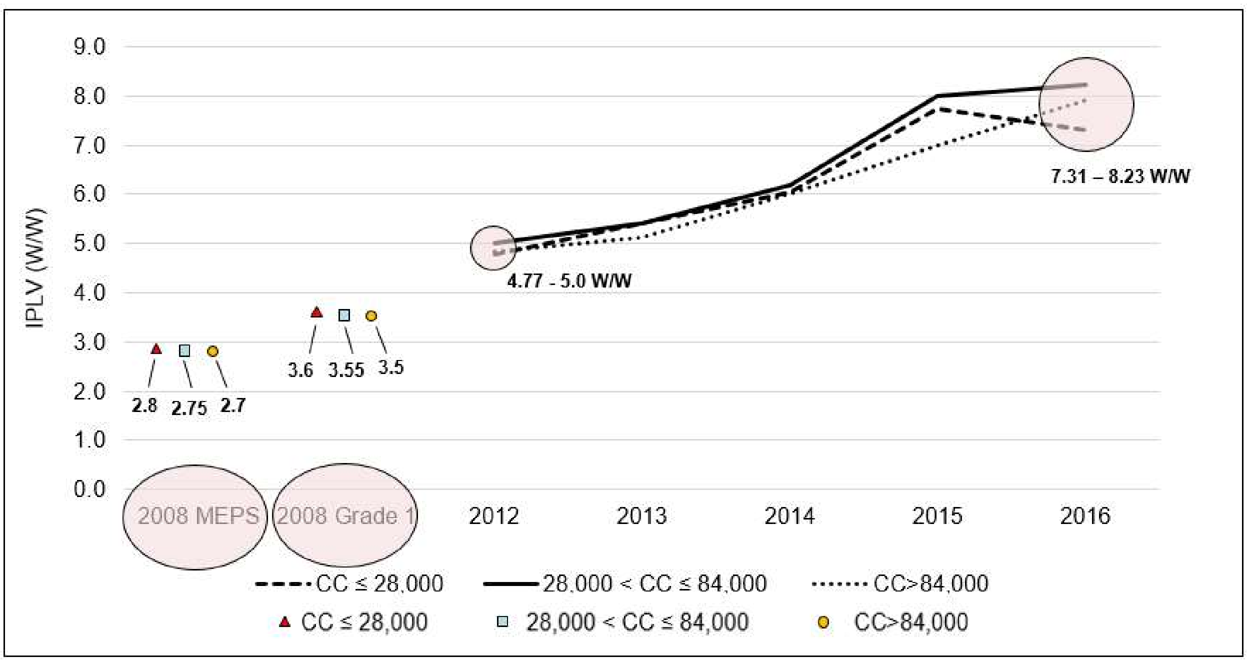


Figure 2. Model-weighted average IPLV for multi-split ACs in China, 2012–2016, compared with 2008 MEPS and Grade 1 values
Source: GB 21454-2008 (2008), Cheng (2017)

The average efficiency of PACs in Japan, including VRF systems, increased by about 30% between 2007 and 2015, from Japanese annual performance factor (Japanese APF) 4.8 to 6.1 (Figure 3). Currently, the best available VRF systems in Japan achieve Japanese APF 6.5–6.6. In general, the best available VRF systems available in major economies surpass the highest efficiency levels recognized by labeling programs by at least 20%. Our preliminary estimates show that best available technology (BAT) VRF systems in Japan have efficiencies in China APF of roughly 5.0-5.5. Table 2 summarizes some of the BAT VRF systems that are manufactured in China along with their system EER ratings. As can be seen, there are multiple VRF systems below 28 kW CC that have system EER ratings of 4.00 and higher. In addition, Table 3 lists reported APF values from Chinese manufacturers for some VRF models. According to the ratings in Table 3, models which have an IPLV range of 6.05-6.60 are reported to have a China APF range of 4.60-5.00.

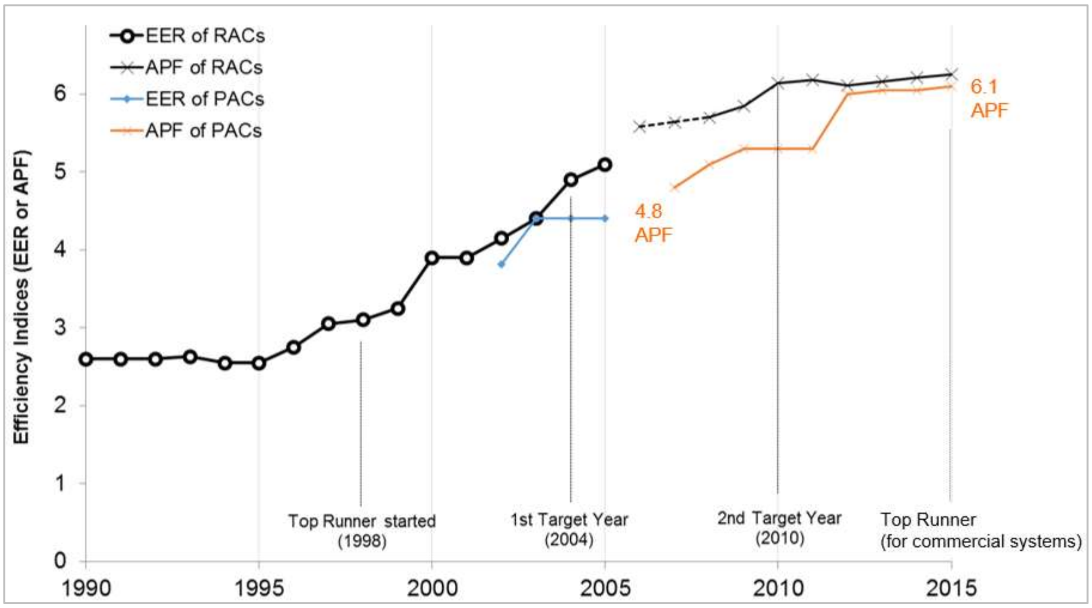


Figure 3. Average efficiency improvement of PACs and room ACs (RACs) in Japan, 1990–2015
Note: Japan under its Top Runner Program has set energy efficiency goals of end-use products based on the most efficient products on the market. In Japan, PACs include commercial-use medium/large split, remote condenser type, single packaged, VRF, and unitary systems. APF calculations for RACs and PACs are based on JIS C 9612 and JIS B 8616, respectively.
Source: Phadke et al. (2017) and Kimura (2010) for RACs; Yoshida (2017) for PACs

Table 2. Some of the BAT VRF systems from Chinese manufacturers and system EER ratings

Brand	Model	CC (kW)	System EER (W/W)
Haier	AV08IMVEVA	25.2	4.50
Chigo	CMV-D252W/XR1	25.2	4.50
Haier	AV08IMVURA	22.4	4.40
Chigo	CMV-D252W/ZR1-C	25.2	4.35
Midea	MV5-X252W/V2GN1	25.2	4.35
Haier	AV08NMMEUA	25.2	4.35
Tica	TIMS080AST	25.0	4.33
Haier	AV08IMSEVA	25.2	4.32
Gree	GMV5S 224WM/B	22.0	4.31
Chigo	CMV-D252W/XR2	28.0	4.30
Haier	AV08GMVESA	25.2	4.25
Haier	AU042FPERA	12.6	4.05
Tica	TIMS125AHT	12.5	4.03

Note: Gree GMV5S 224WM/B, 22 kW CC/EER 4.31/IPLV 9.7.
Source: Haier (2018&2019), Chigo (2018), Midea (2017), Tica (2018), Gree (2019)

Table 3. Some of the reported APF values from Chinese manufacturers[1]

Brand	Model	CC (kW)	APF (Wh/Wh)	IPLV (W/W)
Midea	MDS-H100W (E1)	10.0	5.00	6.6
Midea	MDS-H120W(E1)	12.0	4.95	6.4
Midea	MDVH-V120W / N1-TR (F1)	12.0	4.95	6.4
Midea	MDS-H140W (E1)	14.0	4.90	6.2
Midea	MDS-H160W(E1)	15.5	4.70	6.1
Aux	DLR-H180W (C1)	18.0	4.60	6.05

This report provides context for assessing China's MEPS for VRF systems by analyzing the cost of efficiency improvements via various technological advancements for four VRF systems, which differ based on their capacities and numbers of indoor units. We also estimate payback periods and net customer savings through the lifetimes of the equipment.

2. Definition of VRF Systems

VRF systems are enhanced versions of multi-split AC systems, integrating a large number of indoor units with one outdoor unit, with each indoor unit having its own regulation system. As for traditional multi-split systems, VRF systems can be air cooled, water cooled, cooling only, heating only, or reversible, and they can be able to generate heating and cooling simultaneously (REHVA, 2014). The main difference is that VRF systems are designed for larger systems (up to 50 indoor units), while the traditional multi-split systems are generally practical for 2-8 indoor units. In addition, VRF systems have better tubing for efficient flow of refrigerant so that there are much lesser energy losses. The outdoor unit has one or more compressors that are connected with each other to increase the capacity of the system. These types of systems typically include compressors with variable-speed drives (VSDs, also known as inverter-driven

[1] https://list.jd.com/list.html?cat=737,794,13701

compressors), electronic expansion valves in each indoor unit, and the refrigerant R410A. The outdoor units and each of the indoor units are connected with the refrigerant pipes. The term "variable refrigerant flow" refers to the system's ability to control the amount of refrigerant flowing to each of the evaporators, enabling the use of many evaporators of differing capacities and configurations, individualized comfort control, simultaneous heating and cooling in different zones, and heat recovery from one zone to another (Amarnath and Blatt, 2008). As each indoor unit sends a demand to the outdoor unit, the outdoor unit delivers the amount of refrigerant needed to meet the individual requirements of each indoor unit. The CCs of VRF systems are generally 10–56 kW for single modules, whereas combined systems with multiple outdoor and indoor units can have CCs up to 150 kW (REHVA, 2014). The CCs of indoor units are generally 2–7 kW.

3. Relationship between APF and IPLV

China has been evaluating the energy performance of fixed-speed drive (FSD) RACs using EER while evaluating VSD RACs using SEER for cooling-only products and APF for reversible-type products (HPs). The upcoming MEPS and labels for Chinese RACs will be based on SEER (cooling-only) or APF (reversible) for both FSD and VSD products, starting around July 1, 2020 (Karali et al., 2019).

For evaluating the energy performance of multi-split systems, including VRF systems, China has been using IPLV to set MEPS and labeling requirements. The IPLV metric for air-cooled multi-split systems is expected to be replaced by the APF metric to align with China's new RAC standards and labels defined in GB/T 7725-2004 (2004), GB/T 17758-2010 (2010), and GB 21455-2013 (2013). Outdoor temperature bin hours used for calculating seasonal efficiency of an AC system are defined as a set of hours at each outdoor temperature that requires cooling and heating. The water-cooled multi-split systems still use IPLV but with a revised equation. Details of the current performance evaluation metrics and test conditions in China can be found in Appendix A4. Figure shows relationships used in this study to convert between IPLV and China APF. This relationship is based on multiple sources, including Chinese manufacturers reviews and reported values.

At the time of this study, the U.S. DOE's Appliance Standards and Rulemaking Federal Advisory Committee (ASRAC) formed a working group for VRF multi-split air conditioners and heat pumps to negotiate proposed test procedures. The working group, including representatives from VRF manufacturers, energy efficiency advocacy organizations, and other interested parties, agreed to an amended test procedure for VRFs based on the IEER metric (DOE, 2019a), which was subsequently supported by ASRAC. The amended test procedure includes a controls verification procedure (CVP), as outlined in Appendix C of the AHRI 1230-2019 draft test standard (DOE, 2019b). The CVP is derived from JIS B 8616 and its purpose is to determine modulating components' typical range of operation when controlled by the unit under test at conditions consistent with operating conditions (including standard rating conditions) in a laboratory test room. The manual override settings that would be used during steady-state standard rating tests at a given load point would be required to be within the ranges determined by the CVP (DOE, 2019c). The recommended amended VRF test procedure may provide some useful information for future Chinese test procedure development.

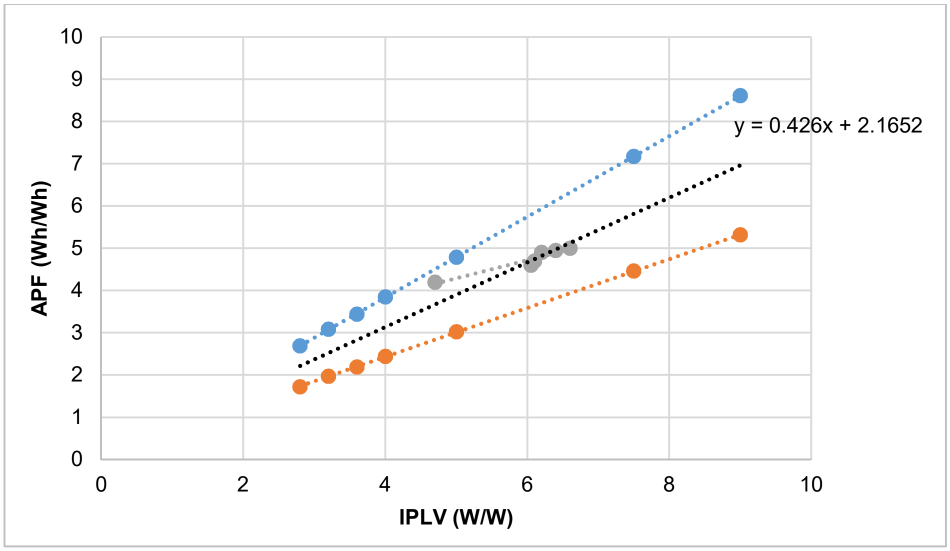


Figure 4. APF-IPLV relationship used in this analysis (gray dots)
Note: The regression relationship represented by the gray dots, based on Chinese manufacturer claims (reviews and reported values), is used in this study. The other three lines in blue (maximum), black (median), and orange (minimum) represent a theoretical range of conversion between IPLV and China APF based on Wu and Ding (2019).

4. Cost of Efficiency Improvement and Consumer Impact Analysis

In this section, we describe our analytical framework and the technologies we consider for improving the efficiency of VRF systems. Shah et al. (2015) and Karali et al. (2019) consider various combinations of efficient technologies used in higher-efficiency RACs to estimate the total incremental cost and financial benefits of efficiency improvements to RAC owners. Their method is similar to those used in the U.S. and EU MEPS rulemaking processes to estimate the incremental cost of appliance efficiency improvements. The method shows the economic costs and efficiency ratings of different combinations of efficient technologies on a cost curve. The analysis in this report follows the same approach to calculate the cost and benefits gained from using technologies that are more efficient in a VRF system. We evaluate 144 different design combinations of efficient technologies for four different VRF systems, based on the most common systems used in China, and estimate the least-cost combinations able to reach certain levels of efficiency. We calculate the overall savings from combined component technologies by multiplying the individual impacts (see Eq. 1).

$$\boldsymbol{t\_es(m) = 1 - \prod_i (1 - es_m(i))} \qquad \text{(Eq.1)}$$

where $t_{es(m)}$ is the overall percent savings of the design combination m and $es_m(i)$ represent the percent energy savings gained from component i used in the design combination m, compared to the baseline component. Please see Karali et al. (2019) for the detailed modeling of the methodology used in this study. We verify the savings potential and incremental cost of the efficient technologies used in this study via multiple VRF manufacturers in China.

In addition, we calculate the net savings from each design combination through the lifetime of the VRF system. These net savings are the sum of the electricity bill savings and the initial investment expenses annualized by means of a discount rate. A payback period for each combination is calculated using the annual electricity bill savings provided by that design combination relative to the baseline. Figure summarizes the method. Key analysis parameters include incremental costs, energy savings, markup rates, hours of use, system lifetime, electricity price, and consumer discount rate.

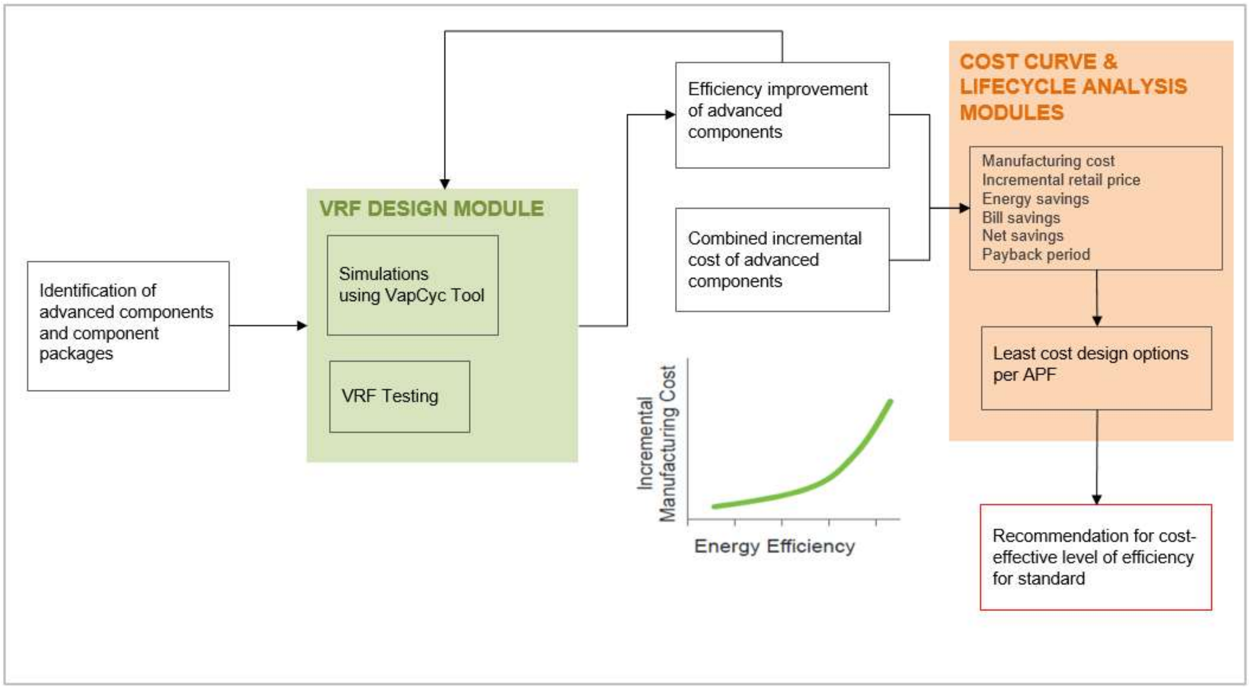


Figure 5. Cost-efficiency curve and consumer impact analysis summary framework

The baseline VRF systems used in this analysis have characteristics typical of such systems:

- Refrigerant R410A
- Inverter scroll compressor
- Electronic expansion valve

The following technologies are considered for increasing the efficiency of VRF systems:

- Compressors with EER ratings increased via approaches such as a specifically designed scroll profile, for example, using asymmetric scroll design, magnet rotor, torque control, smooth 180° sine wave direct current (DC) inverter, brushless DC motor, DC fan motor
- Compressor units with multiple compressors, at least one of which is an inverter-controlled VSD compressor
- Heat exchangers with efficiency increased via approaches such as microchannel heat exchangers, circuit optimization, material change (aluminum, etc.), fin designs, tube designs, and groove patterns

Please see the Appendix A5 for the detailed description of the efficiency improvement options.

4.1. Types of VRF Systems Analyzed and Assumptions

For the cost-efficiency relationships and consumer impact analyses, four different VRF systems are evaluated. According to ChinaIOL (2019), residential small multi-split (CC ≤ 28 kW) accounts for more than 60% in China market. The rest is commercial large units (CC > 28 kW). The most common configurations for residential VRF systems are 14 kW and 18 kW capacities (Khanna et al., 2019). We assume VRF system 1 is representative for systems with CC ≤14 kW, whilst VRF system 2 is representative for systems with 14 kW < CC ≤ 28 kW. We also evaluate two large commercial VRF systems, which have capacities of 40 and 85 kW. Similarly, we assume VRF system 3 is representative for systems with 28 kW < CC ≤ 68 kW, whilst VRF system 2 is representative for systems with 68 kW < CC.

Table 4 summarizes the VRF systems evaluated in this study. Based on discussion with Chinese VRF system manufacturers, we calculate the number of joints, where refrigerant pipes are connected, and additional refrigerant via the following equations:

$$\boldsymbol{number\ of\ joints\ =\ number\ of\ indoor\ units\ -1} \quad \text{(Eq. 2)}$$

$$\boldsymbol{Additional\ refrigerant\ charge\ (kg)\ =\ 0.022\ (kg/m)\ \times\ Ø6.35length\ (m) +\ 0.054\ (kg/m)\ \times\ Ø9.52length\ (m)} \quad \text{(Eq. 3)}$$

In addition, a relation between APF and annual unit energy consumption (UEC) is estimated, based on the performance data of three selected VRF models in accordance with GB21455-2013 (2013). This relationship is then adjusted to calculate UECs for larger capacity systems, also considering the longer hours of use per year in the commercial sector.

Table 4. Characteristics of VRF Systems Analyzed in This Study

	VRF system 1	VRF system 2	VRF system 3	VRF system 4
Refrigerant (R410A) (kg)	4.0	5.1	13.0	26.0
Number of outdoor units	1	1	2	3
Number of indoor units	4	5	16	30
Capacity (BTU/h)	48,000	60,000	136,500	290,000
Capacity (kW)	14	18	40	85
Number of joints	3	4	15	29
Piping length (m)				
Ø9.52	10.0	13.3	50.0	96.7
Ø6.35	20.0	25.0	80.0	150.0
Ø12.70	20.0	13.3	50.0	96.7
Ø15.88	10.0	25.0	80.0	150.0
Additional refrigerant charge (kg)	0.98	1.27	4.46	8.52
APF (Wh/Wh)	4.2	4.2	4.2	4.2
IPLV (W/W)	4.7	4.7	4.7	4.7

Source: Chinese VRF manufacturers

In VRF system 1, the outdoor unit includes one DC inverter, i.e.,VSD, compressor connected to a controller, and the controller is connected to four separate indoor units (Figure).

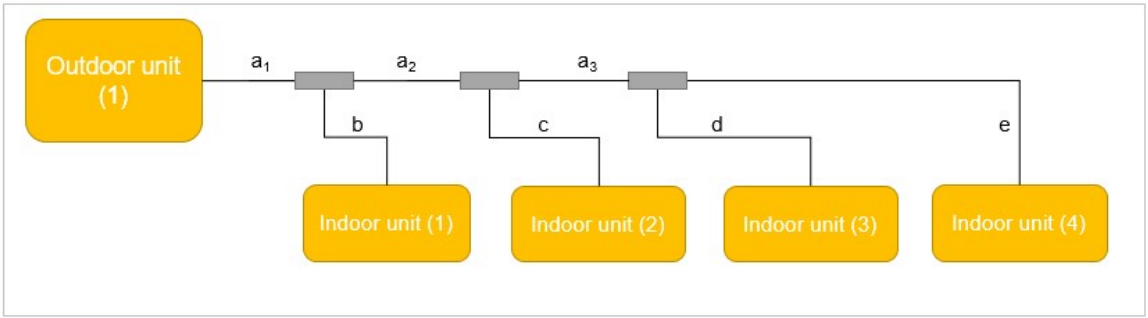


Figure 6. Schematic overview of VRF system 1
Note: This figure is an abstract representation of a 14 kW 1 outdoor/4 indoor unit VRF system and not a one-to-one representation of VRF system 1.
Source: Chinese VRF system manufacturers

In VRF system 2, the outdoor unit includes one DC inverter compressor connected to a controller, and the controller is connected to five separate indoor units (Figure).

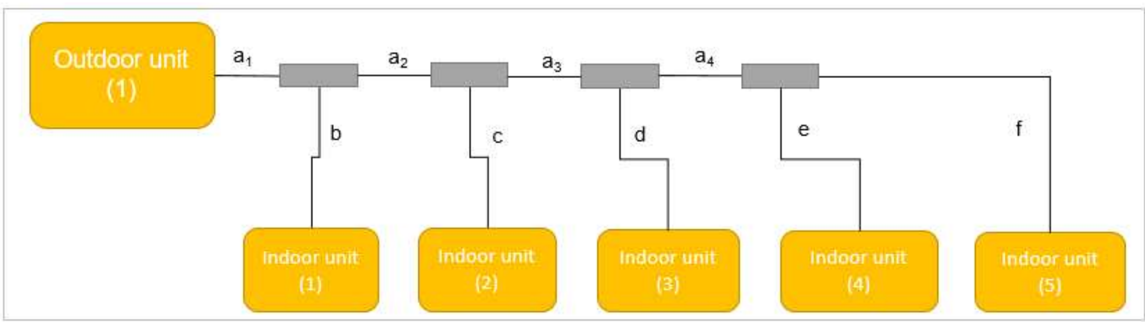


Figure 7. Schematic overview of VRF system 2
Note: This figure is an abstract representation of an 18 kW 1 outdoor/5 indoor unit VRF system and not a one-to-one representation of VRF system 2.
Source: Chinese VRF system manufacturers

In VRF system 3, one outdoor unit has a VSD, and the other has a FSD. Each outdoor unit is connected to a controller, and the controllers are connected to a total of 16 indoor units with capacities varying from 1.8–3.52 kW. In VRF system 4, one outdoor unit has a VSD, and the other two have FSDs. Each outdoor unit is connected to a controller, and the controllers are connected to a total of 30 indoor units with capacities varying from 1.9–7 kW. Figure shows an abstract representation of larger VRF system configurations like systems 3 and 4.

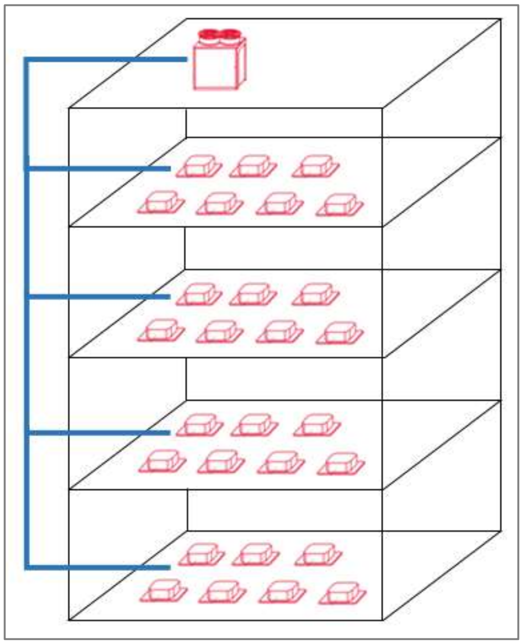


Figure 8. Concept of VRF systems 3 and 4
Note: This figure is an abstract representation of larger VRF system configurations and not a one-to-one representation of VRF system 3 or 4.

4.2. Baseline Cost Structure

Table 5 5 and Figure detail the baseline manufacturing costs, markup rates, taxes, and purchase prices for the four VRF systems analyzed in this study. The most expensive component of a VRF system is the compressor, including inverter chip and electronic control bar costs. The share of compressor cost increases in larger systems owing to the multiple compressors used. The next most expensive components are the heat exchanger and pipeline. The total markup is 68%, covering manufacturer and retailer markups and taxes. The rates are based on input from Chinese VRF system experts and calibration of the model with real market prices. Assembly and installation costs are not included in this analysis because of the difficulty of finding consistent costs across China.

Table 5. VRF System Baseline Costs, Markups, Taxes, and Prices

	VRF system 1	VRF system 2	VRF system 3	VRF system 4
Manufacturing cost ('000 ¥)	12.98	17.38	63.75	127.47
Manufacturer markup	28%			
Retailer markup	28%			
Taxes	12%			
Purchase price ('000 ¥)	21.81	29.20	107.10	214.15

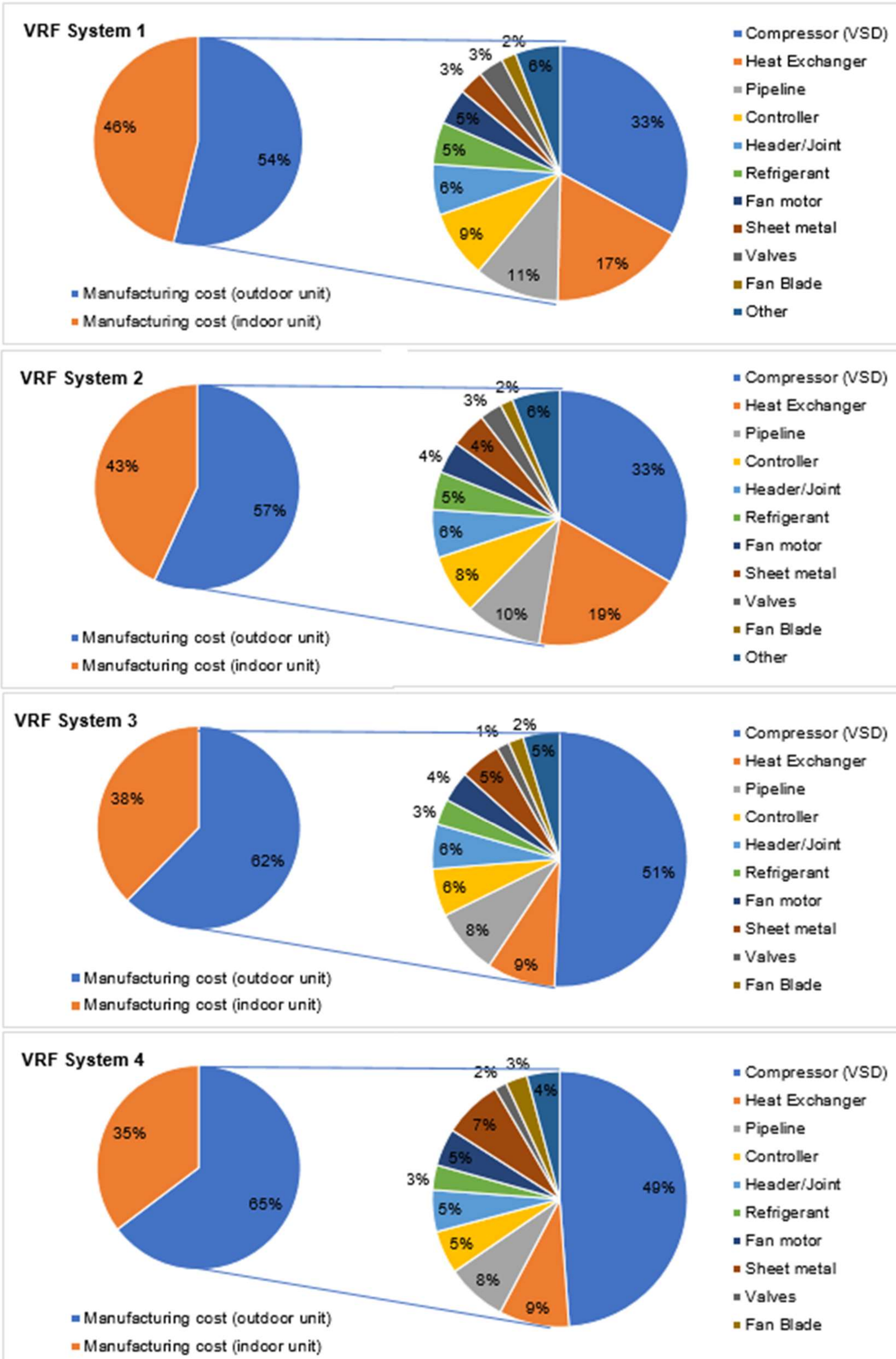


Figure 9. Manufacturing cost details for VRF systems

Source: Chinese VRF manufacturers

Note: Component pie charts on the right side represent the cost share in outdoor unit manufacturing cost.

4.3. Incremental Costs of Efficiency Improvement

The energy savings and cost increase for each efficiency improvement option for VRF system 1 are shown in Table 6. Higher EER rating compressors provide energy savings of 5.9%–15.5% compared with the baseline compressor. We also evaluate design combinations that include two compressors. Compressors 4–7 in Table 6 represent two VSD compressors (24.0% energy savings), while compressors 8–11 represent a combination of one VSD and one FSD compressor (19.2% energy savings). The VSD compressor units are rated at significantly higher part-load efficiency compared with the FSD systems. Energy savings also increase by using an all-DC inverter (5.3%) and more efficient heat exchangers (8.3%–25.8%).

Table 6. Incremental Manufacturing Cost and Energy Savings of Efficient Components for Chinese VRF System 1

	Component	**Manufacturing Cost (￥)**	**Energy Savings from Baseline**
Compressor			
Baseline Compressor	with DC inverter, i.e., VSD	2,300	-
Efficient Compressor 1	with DC inverter, i.e., VSD	2,470	5.9%
Efficient Compressor 2	with DC inverter, i.e., VSD	2,830	11.0%
Efficient Compressor 3	with DC inverter, i.e., VSD	3,190	15.5%
Multiple Compressors 4-7	DC+DC VSD compressors for each design options listed above	2x for each design options listed above	24.0%
Multiple Compressors 8-11	DC VSD + FSD compressors for each design options listed above	1.4x for each design options listed above	19.2%
Inverter			
All DC inverter	DC inverter for fans	460	5.3%
Heat Exchanger (HE)			
Baseline HE	-	1,216	-
Efficient HE 1	UA of both HEs increased by 20%	1,459	8.3%
Efficient HE 2	UA of both HEs increased by 40%	1,702	14.2%
Efficient HE 3	UA of both HEs increased by 60%	1,946	19.0%
Efficient HE 4	UA of both HEs increased by 80%	2,489	22.3%

Source: Costs are based on inputs from Chinese VRF system manufacturers. Energy savings are adjusted from Riviere et al. (2009) based on reported savings change between capacities.
Note: U ($W/m^2/K$) is the overall heat transfer coefficient, A (m^2) is the total heat exchange area. The VRF system with the baseline compressor has a system rating of 3.3 EER.

The energy savings and cost increase for each efficiency improvement option for VRF system 2 are shown in

Table 7. Higher EER rating compressors provide energy savings of 6%–15.5% compared with the baseline compressor. We also evaluate design combinations that include two compressors. Compressors 4–7 in Table 7 represent two VSD VRF compressors (26.0% energy savings), while compressors 8–11 represent a combination of one VSD and one FSD compressor (20.8% energy savings). Energy savings also increase by using an all-DC inverter (5.5%) and more efficient heat exchangers (8.3%–25.8%).

Table 7. Incremental Manufacturing Cost and Energy Savings of Efficient Components for Chinese VRF System 2

	Component	Manufacturing Cost (￥)	Energy Savings from Baseline
Compressor			
Baseline Compressor	with DC inverter, i.e., VSD	3,300	-
Efficient Compressor 1	with DC inverter, i.e., VSD	3,564	6.0%
Efficient Compressor 2	with DC inverter, i.e., VSD	4,122	11.2%
Efficient Compressor 3	with DC inverter, i.e., VSD	4,680	15.5%
Multiple Compressors 4-7	DC+DC VSD compressors for each design options listed above	2x for each design options listed above	26.0%
Multiple Compressors 8-11	DC VSD + FSD compressors for each design options listed above	1.45x for each design options listed above	20.8%
Inverter			
All DC inverter	DC inverter for fans	450	5.5%
Heat Exchanger (HE)			
Baseline HE	-	1,900	-
Efficient HE 1	UA of both HEs increased by 20%	2,280	8.3%
Efficient HE 2	UA of both HEs increased by 40%	2,660	14.2%
Efficient HE 3	UA of both HEs increased by 60%	3,040	19.0%
Efficient HE 4	UA of both HEs increased by 80%	3,895	22.3%

Source: Costs are based on inputs from Chinese VRF system manufacturers. Energy savings are adjusted from Riviere et al. (2009) based on reported savings change between capacities.
Note: U ($W/m^2/K$) is the overall heat transfer coefficient, A (m^2) is the total heat exchange area. The VRF system with the baseline compressor has a system rating of 3.25 EER.

The energy savings and cost increase for each efficiency improvement option for VRF system 3 are shown in

Table 8. Higher EER rating compressors provide energy savings of 6.7%–15.5% compared with the baseline VSD and FSD compressors. We also evaluate design combinations that include two and three VSD compressors. Compressors 4–7 in

Table 8 represent two VSD VRF compressors (12.0% energy savings), while compressors 8–11 represent three VSD VRF compressors (18.0% energy savings). Energy savings also increase by using an all-DC inverter (6.5%) and more efficient heat exchangers (8.3%–26.0%).

Table 8. Incremental Manufacturing Cost and Energy Savings of Efficient Components for Chinese VRF System 3

	Component	Manufacturing Cost (￥)	Energy Savings from Baseline
Compressor			
Baseline Compressor	1xVSD + 1xFSD compressors	20,141	-
Efficient Compressor 1	1xVSD + 1xFSD compressors	22,430	6.7%
Efficient Compressor 2	1xVSD + 1xFSD compressors	24,719	12.7%
Efficient Compressor 3	1xVSD + 1xFSD compressors	27,008	15.5%
Multiple Compressors 4-7	2xVSD compressors for each design options listed above	1.4x for each design options listed above	12.0%
Multiple Compressors 8-11	3xVSD compressors for each design options listed above	2.5x for each design options listed above	18.0%
Inverter			
All DC inverter	DC inverter for fans	1,633	6.5%
Heat Exchanger (HE)			
Baseline HE	-	3,455	-
Efficient HE 1	UA of both HEs increased by 20%	4,150	8.3%
Efficient HE 2	UA of both HEs increased by 40%	4,650	14.3%
Efficient HE 3	UA of both HEs increased by 60%	5,775	19.2%
Efficient HE 4	UA of both HEs increased by 80%	7,082	22.5%

Source: Costs are based on inputs from Chinese VRF system manufacturers. Energy savings are adjusted from Riviere et al. (2009) based on reported savings change between capacities.
Note: U ($W/m^2/K$) is the overall heat transfer coefficient, A (m^2) is the total heat exchange area. The VRF system with the baseline compressor has a system rating of 3.4 EER.

The energy savings and cost increase for each efficiency improvement option for VRF system 4 are shown in

Table 9. Higher EER rating compressors provide energy savings of 7.9%–15.6% compared with the baseline VSD and two FSD compressors. We also evaluate a design combination that combines one VSD with three FSD compressors and a combination that combines two VSD with two FSD compressors. Compressors 4–7 in

Table 9 represent the first combination of compressors (10.0% energy savings), while compressors 8–11 represent the second combination of compressors (22.0% energy savings). Energy savings also increase by using an all-DC inverter (7.0%) and more efficient heat exchangers (8.5%–26.5%).

Table 9. Incremental Manufacturing Cost and Energy Savings of Efficient Components for Chinese VRF System 4

	Component	Manufacturing Cost (￥)	Energy Savings from Baseline
Compressor			
Baseline Compressor	1xVSD + 2xFSD compressors	40,283	-
Efficient Compressor 1	1xVSD + 2xFSD compressors	44,860	7.9%
Efficient Compressor 2	1xVSD + 2xFSD compressors	49,438	14.9%
Efficient Compressor 3	1xVSD + 2xFSD compressors	54,015	15.6%
Multiple Compressors 4-7	2xVSD compressors for each design options listed above	1.4x for each design options listed above	12.0%
Multiple Compressors 8-11	3xVSD compressors for each design options listed above	2.5x for each design options listed above	18.0%
Inverter			
All DC inverter	DC inverter for fans	3,366	7.0%
Heat Exchanger (HE)			
Baseline HE	-	7,331	-
Efficient HE 1	UA of both HEs increased by 20%	8,809	8.5%
Efficient HE 2	UA of both HEs increased by 40%	10,278	14.5%
Efficient HE 3	UA of both HEs increased by 60%	11,746	19.5%
Efficient HE 4	UA of both HEs increased by 80%	15,049	23.0%

Source: Costs are based on inputs from Chinese VRF system manufacturers. Energy savings are adjusted from Riviere et al. (2009) based on reported savings change between capacities.
Note: U ($W/m^2/K$) is the overall heat transfer coefficient, A (m^2) is the total heat exchange area. The VRF system with the baseline compressor has a system rating of 3.0 EER.

4.4. Other Parameters

Operational characteristics of the VRF systems and other parameters used in the analysis are summarized in Table 10. In addition, we have assumed 15 years of lifetime and 4% discount rate. These parameters are the same across all types of VRF systems considered in this analysis.

Table 10. Operational Characteristics of VRF Systems and Other Parameters Used in the Analysis

Parameter	Value	Source
Hours of use (residential) (h/yr)	1,569	GB 21454-20xx
Hours of use (commercial) (h/yr)	1,773	GB/T 18837-2015, GB/T 17758-2010
Electricity price (residential) (￥/kWh)	0.55	China National Development and Reform Commission (NDRC), 2019
Electricity price (commercial) (￥/kWh)	0.8	China National Development and Reform Commission (NDRC), 2019
Annual increase rate of electricity price (%)	1	Assumption in this study
Price sensitivity (± %)	50	Assumption in this study
Usage sensitivity (± %)	25	Assumption in this study

5. Results

Figure 4 and Figure 11 show the modeled least manufacturing costs and retail prices for our VRF systems at efficiencies of 4.2–5.5 APF, with a ± 50% price sensitivity. The x-axis at Figure 10 starts from 2.7 APF to show where the current MEPS is. Figure 4 also presents actual retail prices of 14 kW (1 outdoor/4 indoor units) and 18 kW (1 outdoor/5 indoor units) VRF systems in China to validate our price predictions based on a 68% markup rate. Current market prices appear to reflect the bundling of features other than efficiency, because prices at the same efficiency level vary as much as 100%.

As seen in Figure 4, improving the baseline APF 4.2 to APF 4.5, 5.0, and 5.5 can be achieved at price increases of about 3.2%, 7.7%, and 12.2%, respectively, for VRF system 1. For VRF system 2, the price increases are about 3.7%, 8.5%, and 11.7%. As listed earlier in Table 3, there are already multiple models from Chinese manufacturers reported to have APF rating ranging from 4.6 to 5.0. Improving to APF 5.5—the highest efficiency in the Japanese market for these categories—can be achieved at a price increase of about 12%. APF 5.5 represents a ~30% improvement in efficiency compared to baseline APF 4.2.

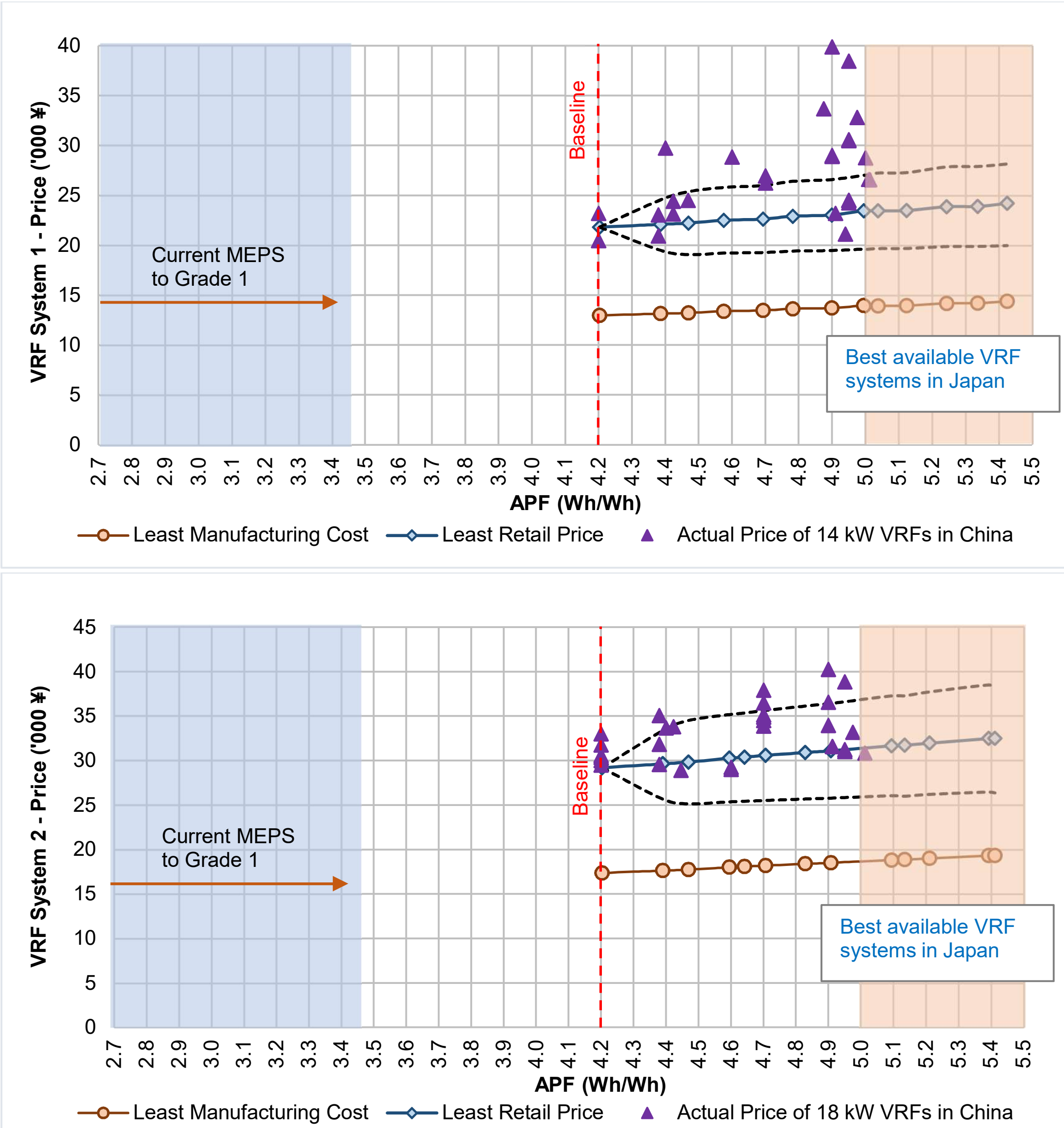
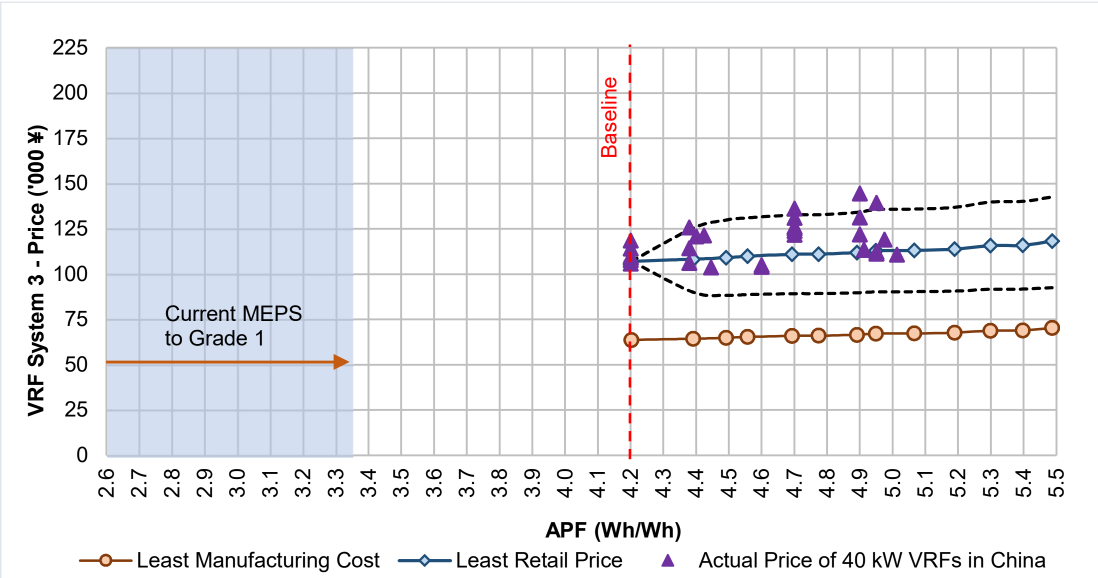


Figure 4. Manufacturing cost and retail price increase per efficiency improvement of VRF Systems 1 and 2

Note: Y-axis scales differ betweeen the two systems. Dotted lines represent the ±50% price sensitivity. High-efficiency VRF systems selected from the Japanese market are estimated to have efficiency in China APF roughly in a range of 5.0-5.5, without any further technical adjustments for each market and reflects uncertainty in conversion. Current MEPS to Grade 1 conversion also includes uncertainty.

For the two larger systems in Figure 5, no real price data are available, because such systems are generally customized for individual building projects, and bulk prices can vary owing to building design and so forth; therefore, we use a scaling factor based on capacity and number of indoor units to obtain representative market prices per DOE (2015). As seen in Figure 5, improving the baseline APF 4.2 to APF 4.5, 5.0, and 5.5 for both systems can be achieved at price increases of approximately 2.5%, 5.5% and 10%, respectively.



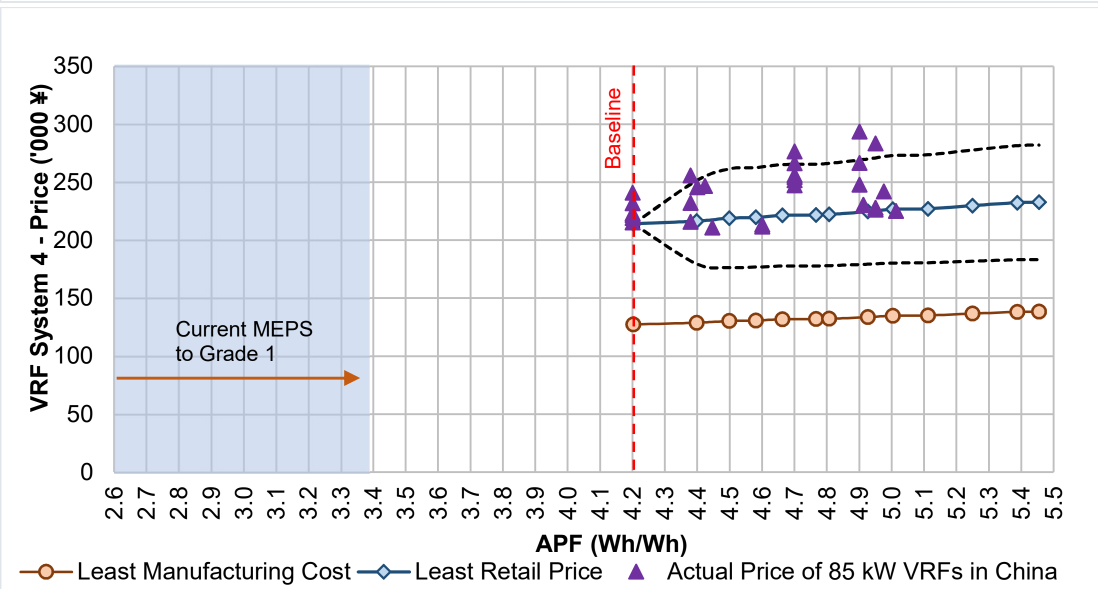


Figure 5. Manufacturing cost and retail price increase per efficiency improvement of VRF systems 3 and 4
Note: Y-axis scales differ between the two systems. Dotted lines represent the ±50% price sensitivity. Current MEPS to Grade 1 conversion includes uncertainty.

Figure 6 shows net customer savings over the lifetimes of VRF systems 1 and 2, based on cumulative discounted electricity bill savings and the incremental cost of higher-efficiency systems. Figure 6 also shows sensitivity lines for a ±25% change in VRF use. Net savings increase with increasing efficiency until the end of the x-axis (APF 5.5) VRF systems 1 and 2. Thus, increasing the MEPS stringency to APF 5.5—the highest efficiency level in the Japanese market for small VRF systems common for residential use—is likely to provide large consumer benefits. Net savings are significantly lower with 25% less use, but still remain positive through APF 5.5.

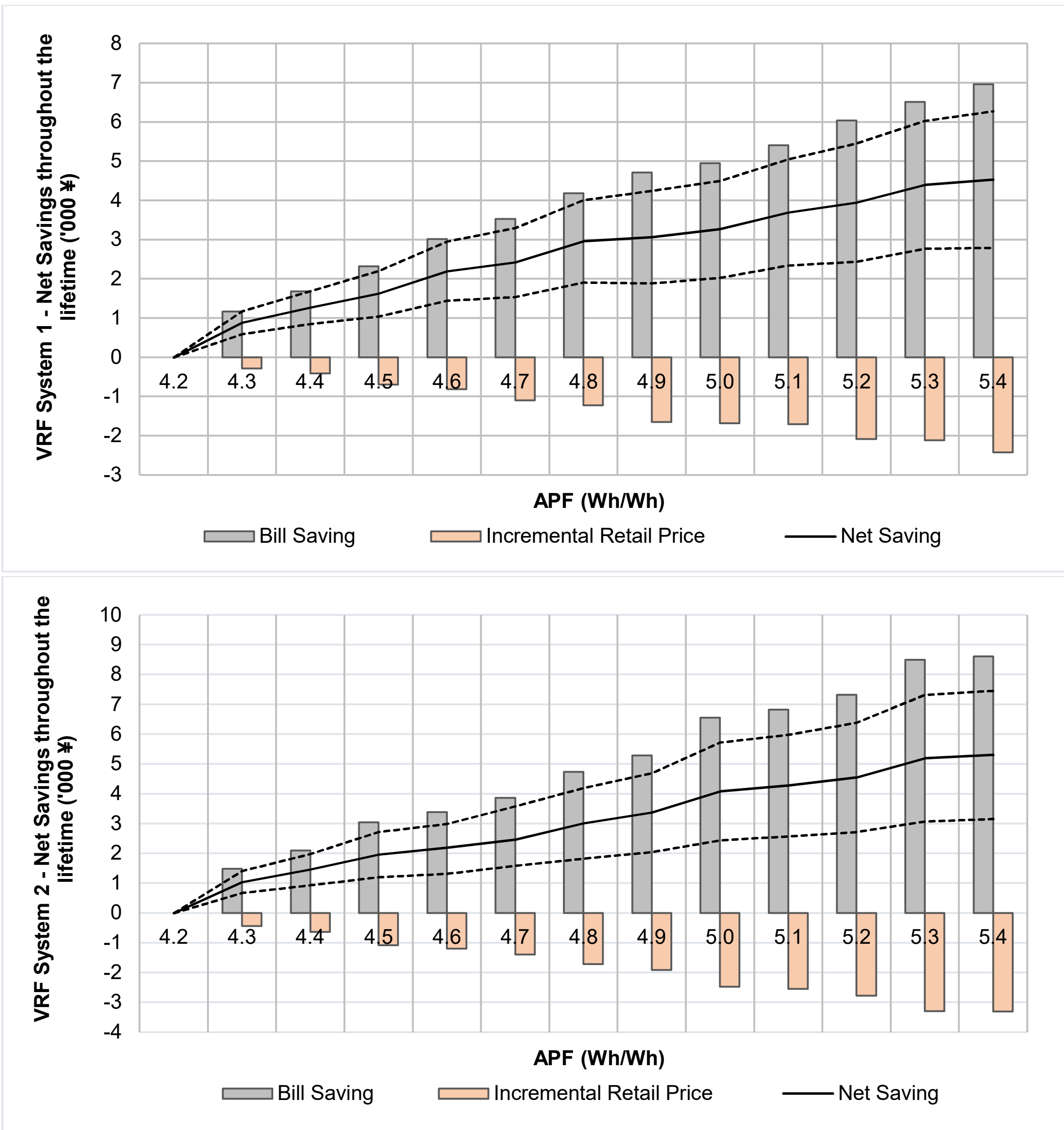


Figure 6. Lifetime net savings for each design level of the least-cost curve for VRF systems 1 and 2 in China
Note: Y-axis scales differ between the two systems. Dotted lines represent ±25% use sensitivity.

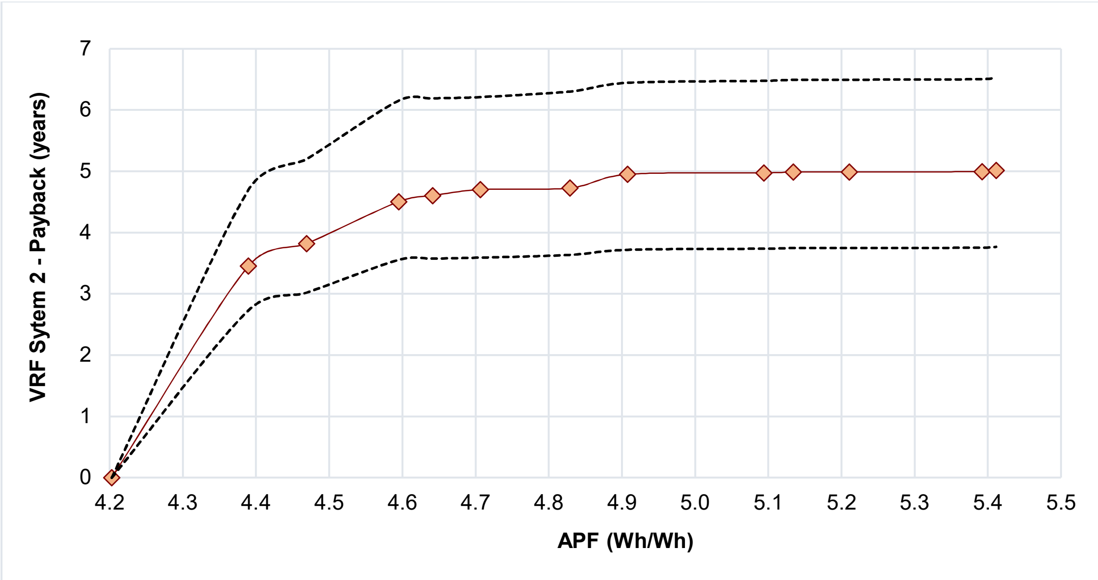


Figure 7 displays the payback periods for VRF systems 1 and 2 at each higher-efficiency design level with a ±25% change in hours of use, compared with the baseline APF 4.2 unit. For VRF system 1, the payback period is less than or equal to 4 years with increasing efficiency until about APF 5.0, and less than or equal to 4.5 years for efficiencies of APF 5.1–5.5. In contrast, VRF system 2 is paid back in less than 4 years only at efficiencies below APF 4.5. The payback period is between 4.5 and 5 years for APF 4.6–5.5. The sensitivity lines in

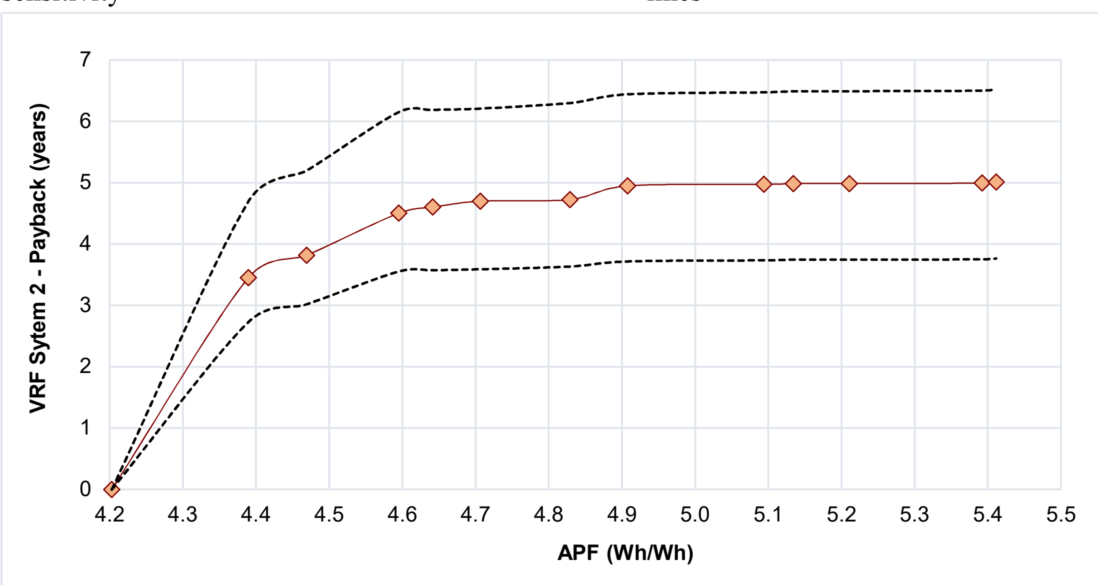


Figure 7 show that 25% less use increases the payback period by more than 1 year, and the difference widens with improving efficiency.

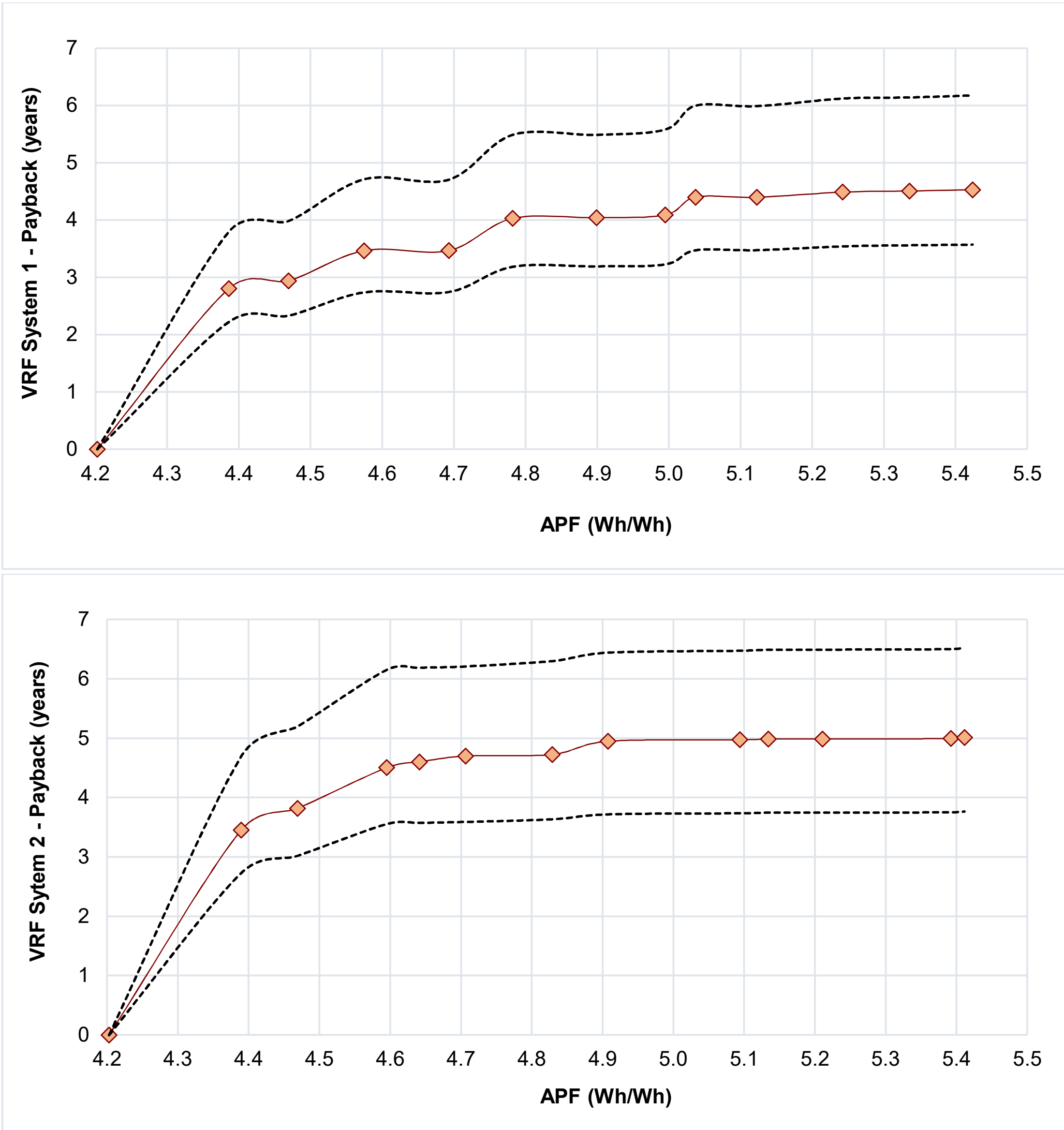


Figure 7. Payback periods for each design level of the least-cost curve for VRF systems 1 and 2 in China
Note: Y-axis scales differ between the two systems. Dotted lines represent the ±25% use sensitivity.

Figure 8 shows net customer savings over the lifetimes of VRF systems 3 and 4, which are the two commercial systems analyzed in this study. Net savings are much higher compared with savings from small-capacity residential VRF systems, and they increase with improving efficiency until the end of the x-axis (APF 5.5). Thus, increasing the MEPS to APF 5.5 for VRF system 3 and 4 likely would provide large benefits to customers. As in residential units, the net savings are significantly lower with 25% fewer hours of use, but they remain positive through APF 5.5.

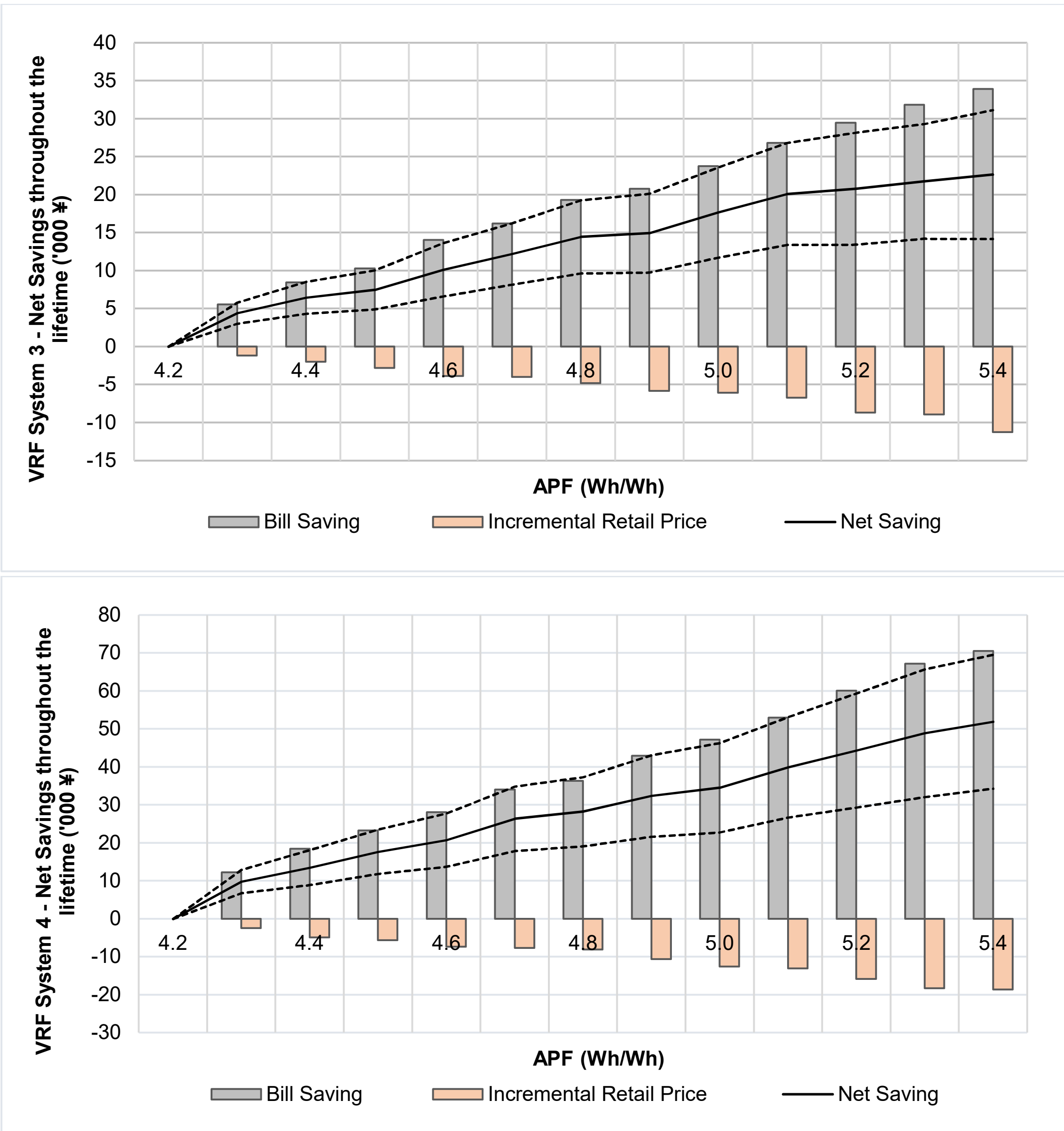


Figure 8. Lifetime net savings for each design level of the least-cost curve for VRF systems 3 and 4 in China
Note: Axis scales differ between the two systems. Dotted lines represent the ±25% use sensitivity.

As seen in Figure 9, large-capacity commercial systems pay back faster than residential systems. As with residential systems, 25% less use increases the payback period, but the magnitude is slightly smaller.

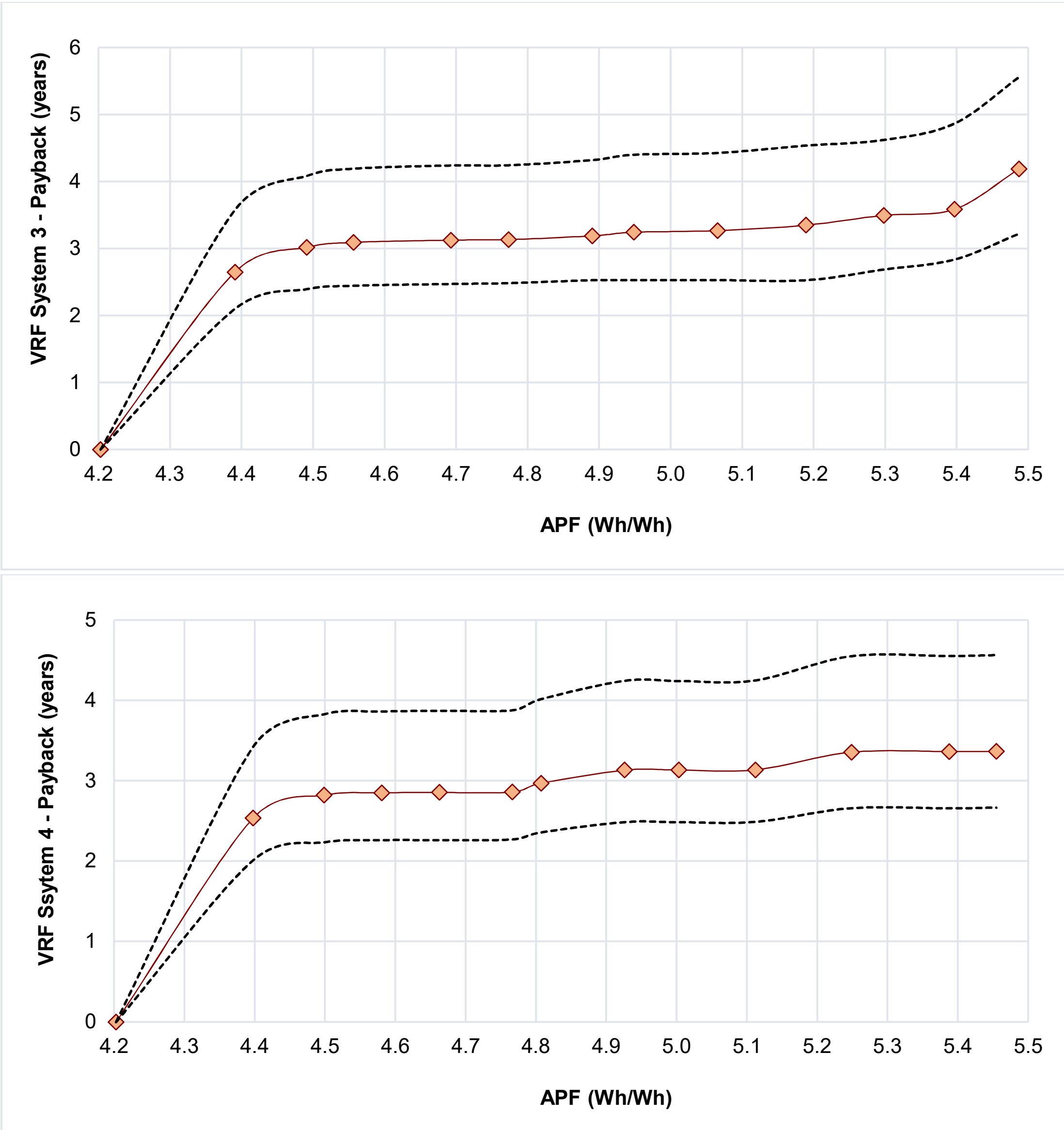


Figure 9. Payback periods for each design level of the least-cost curve for VRF systems 3 and 4 in China

Note: Y-axis scales differ between the two systems. Dotted lines represent the ±25% use sensitivity.

6. Conclusion

This study provides a comprehensive analysis of cost-efficiency relationships for VRF air conditioning systems in China. We examine the cost of efficiency improvements for four different VRF systems, which vary by capacity and number of indoor units. The results show that China has great opportunity to improve its VRF system efficiency using cost-effective technologies. With stringent MEPS levels, sufficient incentives, and robust regulatory programs such as labeling and procurement programs, high-efficiency VRF systems can be developed and deployed in China.

The following are key findings and implications of this study:

- The best available VRF systems in Japan currently achieve Japanese APF 6.5–6.6 (China APF of roughly 5.0-5.5, based on our preliminary estimates). In general, the best available VRF systems available in major economies surpass the highest efficiency levels recognized by labeling programs by at least 20%.
- There are multiple VRF systems manufactured in China that have system EER ratings of 4.00 and higher. In addition, some Chinese manufacturers reported a China APF range of 4.60-5.00 for VRF systems with an IPLV range of 6.05-6.60 (see Table 3).
- Increasing the efficiency of small-capacity VRF systems (considered CC ≤ 28 kW in this report)) to APF 5.5—representing about 30% efficiency improvement, which are common for residential use—is feasible and beneficial. There are already multiple models from Chinese manufacturers reported to have APF rating ranging from 4.6 to 5.0, an APF 5.5—the highest efficiency in the Japanese market for these categories
    - could be achieved at a price increase of about 12%, compared with the price of a baseline APF 4.2 VRF system.
    - likely would provide large consumer benefits in the form of net savings over a system's lifetime; the payback period varies little between efficiency levels of APF 5.0 and 5.5, and is less than 5 years in most of the cases.
- Increasing the efficiency of large-capacity VRF systems (common for commercial use) to APF 5.5 for systems is also feasible and beneficial.
    - It could be achieved at a price increase of about 10%, compared with the price of a baseline APF 4.2 VRF system.
    - It likely would provide large benefits to commercial customers in the form of net savings over a system's lifetime, and it could pay back faster than residential units do because of longer hours of use.

References

Air-conditioning, Heating and Refrigeration Institute (AHRI)-1230. 2010. *AHRI Standard 1230-2010 Standard for Performance Rating of Variable Refrigerant Flow (VRF) Multi-Split Air-Conditioning and Heat Pump Equipment*. http://www.ahrinet.org/App_Content/ahri/files/standards%20pdfs/AHRI%20standards%20pdfs/AHRI%20Standard%201230%20-%202010.pdf

ANSI/AHRI 340/360-2007. *Performance Rating of Commercial and Industrial Unitary Air-Conditioning And Heat Pump Equipment.* (With Addenda 1 And 2)

Amarnath, A., Blatt, M. 2008. "Variable Refrigerant Flow: An Emerging Air Conditioner and Heat Pump Technology." *2008 ACEEE Summer Study on Energy Efficiency in Buildings*.

BSRIA (2016). *Large Packaged 2016 – China*. Report 59008/5C. Bracknell, UK: BSRIA.

Cheng, J. 2017. *Survey and Study Report on Application for Refrigeration and Air Conditioning Products in China*. In Chinese. Beijing: China Zhijian Publishing House.

Chigo. 2018. *DC Inverter VRF System CAC Catalogue*.

ChinaIOL. 2019. *2019 China Multi-split Air Conditioner (Heat Pump) Energy Efficiency Survey' Progress Presentation*. April, Beijing, China {In Chinese}.

DOE (U.S. Department of Energy). 2015. *Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Small, Large, and Very Large Commercial Package Air Conditioning and Heating Equipment*. Washington, DC: DOE.

DOE. 2016. *Title 10: Energy, §431.97 Energy Efficiency Standards and Their Compliance Dates*. Washington, DC: DOE.

DOE. 2017. *10 CFR Part 430, Energy Conservation Program: Energy Conservation Standards for Residential Central Air Conditioners and Heat Pumps*. Washington, DC: DOE.

DOE. 2019a. *2019-10-01 Appliance Standards and Rulemaking Federal Advisory Committee Variable Refrigerant Flow Working Group Test Procedure Term Sheet.* October 1, 2019. https://www.regulations.gov/document?D=EERE-2018-BT-STD-0003-0044

DOE. 2019b. *Draft 9/20/2019 2019 Standard for Performance Rating of Variable Refrigerant Flow (VRF) Multi-Split Air-Conditioning and Heat Pump Equipment (AHRI Standard 1230 (I-P))*. https://www.regulations.gov/document?D=EERE-2018-BT-STD-0003-0057

DOE. 2019c. *Report to VRF ASRAC WG from Controls Verification Test Subcommittee*. April 17, 2019. https://www.regulations.gov/document?D=EERE-2018-BT-STD-0003-0034

GB 21454-2008. 2008. *The Minimum Allowable Values of the IPLV and Energy Efficiency Grades for Multi-Connected Air-Condition (Heat Pump) Unit*. AQSIQ and SAC.

GB 21455-2013. 2013. *Minimum Allowable Values of the Energy Efficiency and Energy Efficiency Grades for Variable Speed Room Air Conditioners*. Standards Press of China, Beijing.

GB 21454-20xx. Draft. *Minimum Allowable Values of the Energy Efficiency and Energy Efficiency Grades for Multi-Connected Air-Condition (Heat Pump) Units*. AQSIQ and SAC.

GB/T 17758-2010. 2010. *Unitary Air Conditioners*. AQSIQ and SAC.

GB/T 17758-1999. 1999. *Unitary air conditioners*. AQSIQ, published on 5/25/1999, effective 12/1/1999.

GB/T 17758-2010. 2010. *Unitary air conditioners*. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ) and Standardization Administration of China (SAC), published on 9/26/2010, effective 2/1/2011, replace GB/T 17758-1999.

GB/T 18837-2002. 2002. *Multi-connected air conditioner (heat pump) unit*. AQSIQ, published on 9/11/2002, effective 04/01/2003.

GB/T 18837-2015. 2015. *Multi-connected air conditioner (heat pump) unit.* AQSIQ and SAC, published on 12/10/2015, effective 7/1/2016, replace GB/T 18837-2002.

GB/T 18837-2015. 2015. *Multi-Connected Air Conditioner (Heat Pump) Unit*. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ) and Standardization Administration of the People's Republic of China (SAC).

GB/T 7725-2004. 2004. *Room air conditioners*. AQSIQ and SAC, published on 12/2/2004, effective 3/1/2005, replace GB/T 7725-1996.

Gree. 2019. *Multi-line Series*. http://www.gree.com.cn/pczwb/cpzx/greezykt/syzykt/dljxl/detail-1224.shtml

Haier. 2018. *MRV 2018 General Catalogue Commercial Air Conditioning*.

Haier. 2019. *MRV 2019 General Catalogue Commercial Air Conditioning*.

JIS (Japanese Industrial Standards). 2013. *JIS C 9612: 2013 ルームエアコンディショナ (room air conditioner)*. Japan Society of Mechanical Engineers.

JIS. 2015. *JIS B 8616: 2015 パッケージエアコンディショナ (package air conditioner)*. Japan Society of Mechanical Engineers.

Karali, N., Shah, N., Park, W.Y., Khanna, N., Ding, C., Lin, J., Zhou, N. *Improving the Energy Efficiency of Room Air Conditioners in China: Costs and Benefits*. Applied Energy, Volume 258, 15 January 2020, 114023

Khanna, N., Ding, C., Park, W.Y., Shah, N., Lin, J. 2019. *Market Assessment of Multi-split Air Conditioning Systems in the Chinese and Global Market*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Kimura, O. 2010. *Japanese Top Runner Approach for Energy Efficiency Standards*. SERC09035, Socio-Economic Research Center (SERC) Discussion Paper.

Midea. 2017. *Commercial Air Conditioners. R410A All DC Inverter VRF V5 X Series 50/60Hz*.

Phadke, Amol, Won Young Park, Nikit Abhyankar, Nihar Shah. 2017. *Relationship between Appliance Prices and Energy-Efficiency Standards and Labeling Policies: Empirical Evidence from Residential Air Conditioners*. Presented at 9th International Conference on Energy Efficiency in Domestic Appliances and Lighting (EEDAL).

Shah, N., Wei, M., Letschert, V., Phadke, A. *Benefits of Leapfrogging to Super Efficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. Berkeley CA: Lawrence Berkeley National Laboratory report LBNL-1003671; 2015.

REHVA. 2014. *The REHVA European HVAC Journal*. Special issue for ACREX India 2014 exhibition.

Tica. 2018. *TICA Inverter VRF System*.

Thornton, B., Wagner, A. 2012. *Variable Refrigerant Flow Systems*. Richland, WA: Pacific Northwest National Laboratory.

Wu, G., Ding, G. 2019. "Comparative Analysis of Energy Efficiency Metrics IPLV and APF for Multi-split Air Conditioner Units." Shanghai Jiaotong University. Presented to the China National Institute of Standardization, April, Beijing, China.

Yoshida, Y. 2017. Study of Packaged Air-conditioners Intended to Improve Annual Efficiency. Hokkaido University. Doctoral thesis. DOI: 10.14943/doctoral.k12767

Appendix

A1. Definitions of Key Product Categories in BSRIA market research

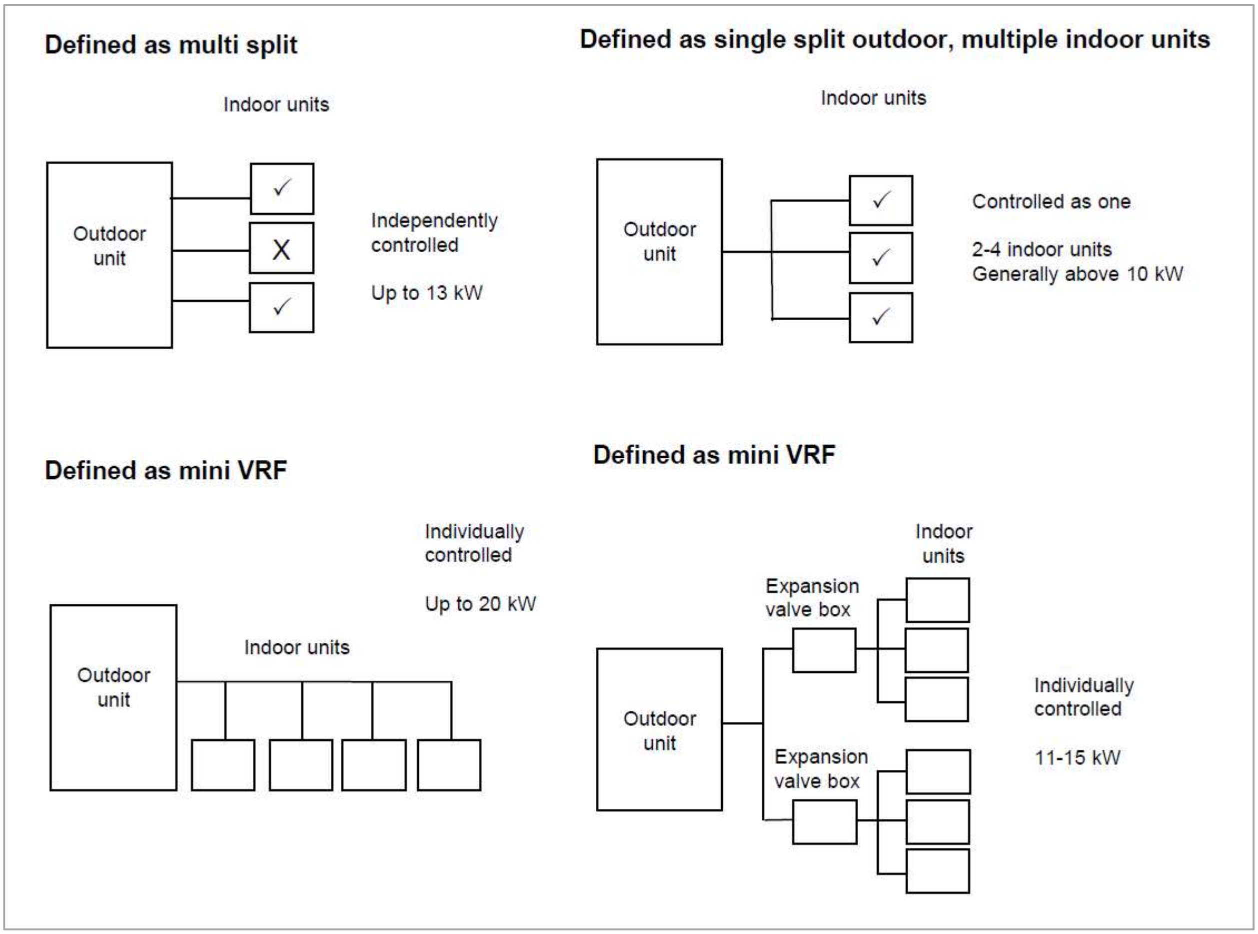


Figure A1-1. Definitions of PAC product types in China market.
Source: BSRIA (2016)

A2. U.S. Single-Phase, CC < 19 kW VRF Multi-Split ACs and HPs: SEER and EER for Cooling and Heating Seasonal Performance Factor (HSPF) for Heating

The U.S. residential central ACs/HPs MEPS (Table A), which also covers single-phase CC<19 kW VRF multi-split units, divides the country into three different climate zones based on the population-weighted number of heating degree days (HDD); see **Error! Reference source not found.**:

- < 5,000 HDD_{65F}: Southeast (hot-dry), Southwest (hot-humid) based on the number of cooling operating hours and relative humidity during those operating hours per year
- ≥ 5,000 HDD_{65F}: North (also referred to as "rest of the country"), which represents the national standard

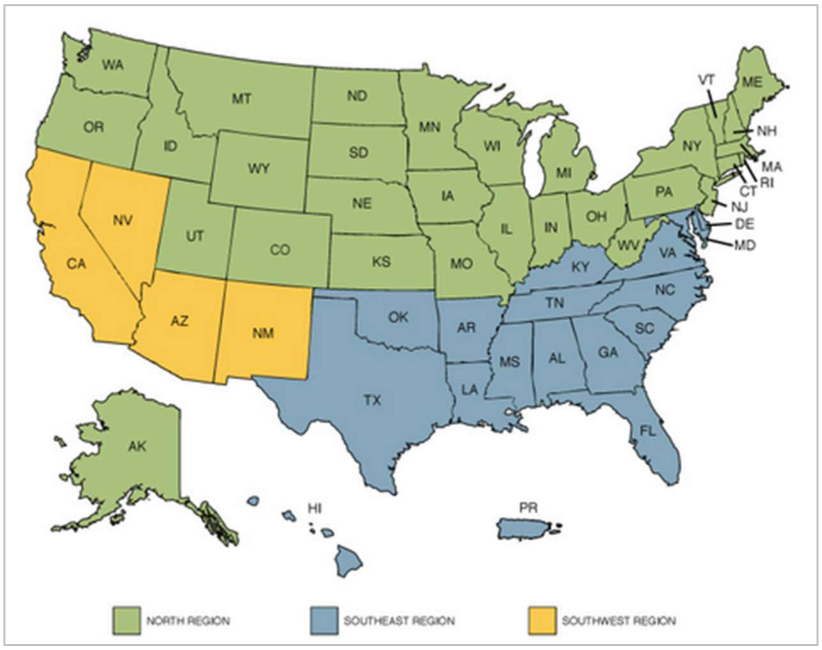


Figure A2-1. U.S. climate zones used in the residential central ACs/HPs MEPS

Table A2-1. 2015 Version of U.S. Residential Central ACs/HPs MEPS, Including Single-Phase CC<19 kW VRF Multi-Split Units

	North (National)		Southeast	Southwest	
	SEER	**HSPF**	**SEER**	**SEER**	**EER**
Split AC (< CC 45,000 Btu/h)	14	NA	15	15	12.2/10.2
Split AC (≥ CC 45,000 Btu/h)	14	NA	14.5	14.5	11.7/10.2
Split HPs	15	8.8	NA	NA	NA
Single-package ACs	14	NA	NA	NA	11.0
Single-package HPs	14	8.0	NA	NA	NA

Source: DOE (2017)
Note: Single-phase, CC < 19 kW VRF multi-split units follow the residential central ACs/HPs MEPS. The 10.2 EER amended energy conservation standard applies to split-system ACs with a SEER greater than or equal to 16.

A3. U.S. Other VRF Multi-Split ACs and HPs: SEER/EER for Cooling and HSPF/Coefficient of Performance (COP) for Heating

In the United States, there is no climate division for VRF systems larger than 19 kW. The same MEPS is used for different climatic regions (Table A).

Table A3-1. U.S. MEPS for VRF Multi-Split ACs and HPs

Equipment Type	CC	Heating Type	Efficiency Level	Compliance Date: Products Manufactured on and After
VRF multi-split ACs (air-cooled)	< 65,000 Btu/h ≥ 65,000 Btu/h and < 135,000 Btu/h	All No heating or electric resistance heating	13.0 SEER 11.2 EER	June 16, 2008 Jan 1, 2010
		All other types of heating	11.0 EER	Jan 1, 2010
	≥ 135,000 Btu/h and < 240,000 Btu/h	No heating or electric resistance heating	11.0 EER	Jan 1, 2010
		All other types of heating	10.8 EER	Jan 1, 2010
	≥ 240,000 Btu/h and < 760,000 Btu/h	No heating or electric resistance heating	10.0 EER	Jan 1, 2010
		All other types of heating	9.8 EER	Jan 1, 2010
VRF multi-split HPs (air-cooled)	< 65,000 Btu/h	All	13.0 SEER 7.7 HSPF	Jun 16, 2008
	≥ 65,000 Btu/h and < 135,000 Btu/h	No heating or electric resistance heating	11.0 EER 3.3 COP	Jan 1, 2010
		All other types of heating	10.8 EER 3.3 COP	Jan 1, 2010
	≥ 135,000 Btu/h and < 240,000 Btu/h	No heating or electric resistance heating	10.6 EER 3.2 COP	Jan 1, 2010
		All other types of heating	10.4 EER 3.2 COP	Jan 1, 2010
	≥ 240,000 Btu/h and < 760,000 Btu/h	No heating or electric resistance heating	9.5 EER 3.2 COP	Jan 1, 2010
		All other types of heating	9.3 EER 3.2 COP	Jan 1, 2010
VRF multi-split HPs (water-source)	< 17,000 Btu/h	Without heat recovery	12.0 EER 4.2 COP	Oct 29, 2012 Oct 29, 2003
		With heat recovery	11.8 EER 4.2 COP	Oct 29, 2012 Oct 29, 2003
	≥ 17,000 Btu/h and < 65,000 Btu/h	All	12.0 EER 4.2 COP	Oct 29, 2003
	≥ 65,000 Btu/h and < 135,000 Btu/h	All	12.0 EER 4.2 COP	Oct 29, 2003
	≥ 135,000 Btu/h and < 760,000 Btu/h	Without heat recovery	10.0 EER 3.9 COP	Oct 29, 2013
		With heat recovery	9.8 EER 3.9 COP	Oct 29, 2013

Source: DOE (2016)
Note: VRF multi-split HPs (air-cooled) with heat recovery fall under the category of "all other types of heating" unless they also have electric resistance heating, in which case they fall under the category of "no heating or electric resistance heating."

A4. Performance Evaluation Metrics and Test Conditions

IPLV is a single number that is a cooling part-load efficiency figure of merit calculated per the method defined by the AHRI in ANSI/AHRI 340/360-2007, AHRI 1230-2010, and so on. In China, GB/T 17758-1999 and GB/T 18837-2002 specified the IPLV and test procedure consistent with the AHRI standard. Systems which are capable of capacity reduction are rated at 100% and at three steps of capacity reduction (close to 75%, 50%, 25%) provided by the manufacturer. IPLV is calculated as follows:

a. Determine the capacity and EER at the conditions specified in the standard.
b. Determine the part load factor (PLF) at each rating point specified in the standard
c. Use the following equation to calculate IPLV

$$IPLV = \left(PLF_1 - PLF_2\right) \times \frac{\left(EER_1 + EER_2\right)}{2} + \left(PLF_2 - PLF_3\right) \times \frac{\left(EER_2 + EER_3\right)}{2} + \cdots$$
$$+ \left(PLF_{n-1} - PLF_n\right) \times \frac{\left(EER_{n-1} + EER_n\right)}{2} + \left(PLF_n\right) \times \left(EER_n\right)$$

where:

PLF = part-load factor
n = total number of capacity steps

In general, IPLV is calculated using the general equation with: n = 4 and

PLF1 = 1.0 EER1 = 8.9 (US), 2.9 (China)
PLF2 = 0.9 EER2 = 7.7 (US), 4.05 (China)
PLF3 = 0.4 EER3 = 7.1 (US), 5.14 (China)
PLF4 = 0.1 EER4 = 5.0 (US), 2.57 (China)

Those two standards were revised and replaced by GB/T 17758-2010 and GB/T 18837-2015. In the latest version, IPLV is only used for water-cooled multi-split units, while APF is used for air-cooled units. The revised IPLV is similar to the IEER in AHRI 1230-2010, but with different weighting coefficients and load curves (condensing temperature over % load). The new China IPLV is calculated using test derived data and the following formula.

$$IPLV = 2.3\% \times A + 41.5\% \times B + 46.1\% \times C + 10.1\% \times D$$

For VRF multi-split ACs $\geq$ 19 kW (65,000 Btu/h), the AHRI IEER is calculated using the following coefficient and formula.

$$IEER = (0.020 \cdot A) + (0.617 \cdot B) + (0.238 \cdot C) + (0.125 \cdot D)$$

where:

A = EER at 100% net capacity at AHRI standard rating conditions
B = EER at 75% net capacity and reduced ambient
C = EER at 50% net capacity and reduced ambient
D = EER at 50% net capacity and reduced ambient

Table A4-1. Operating Conditions for Standard Rating and Performance Operating Tests for Systems ≥ 19,000 W (65,000 Btu/h) in AHRI 1230-2010

	TEST	INDOOR SECTION		OUTDOOR SECTION					
		Air Entering		Air Entering				Water[5]	
				Air Cooled		Evaporative			
		Dry-Bulb °F [°C]	Wet-Bulb °F [°C]	Dry-Bulb °F [°C]	Wet-Bulb °F [°C]	Dry-Bulb °F [°C]	Wet-Bulb °F [°C]	IN °F [°C]	OUT °F [°C]
COOLING	Standard Rating Conditions Cooling[3]	80.0 [26.7]	67.0 [19.4]	95.0 [35.0]	75.0[1] [23.9]	95.0 [35.0]	75.0 [23.9]	85.0 [29.4]	95.0 [35.0]
COOLING	Low Temperature Operating Cooling[3]	67.0 [19.4]	57.0 [13.9]	67.0 [19.4]	57.0[1] [13.9]	67.0 [19.4]	57.0 [13.9]	NA	70.0[2] [21.1]
COOLING	Maximum Operating Conditions[3]	80.0 [26.7]	67.0 [19.4]	115 [46.1]	75.0[1] [23.9]	100 [37.8]	80.0[4] [26.7]	90.0[2] [32.2]	NA
COOLING	Part-Load Conditions (IEER)[3]	80.0 [26.7]	67.0 [19.4]	Varies with load per Table 11	[1]Varies with load per Table 11	Varies with load per Table 11	Varies with load per Table 11	[2]Varies with load per Table 11	Varies with load per Table 11
COOLING	Part-Load Conditions (IPLV)[3]	80.0 [26.7]	67.0 [19.4]	80.0 [26.7]	67.0[1] [19.4]	80.0 [26.7]	67.0 [26.7]	75.0[2] [23.9]	NA
COOLING	Insulation Efficiency[3]	80.0 [26.7]	75.0 [23.9]	80.0 [26.7]	75.0[1] [23.9]	80.0 [26.7]	75.0 [23.9]	NA	80.0 [26.7]
COOLING	Condensate Disposal[3]	80.0 [26.7]	75.0 [23.9]	80.0 [26.7]	75.0[1] [23.9]	80.0 [26.7]	75.0 [23.9]	NA	80.0 [26.7]
HEATING	Standard Rating Conditions (High Temperature Steady State Heating)	70.0 [21.1]	60.0 [15.6] (max)	47.0 [8.3]	43.0 [6.1]	NA	NA	NA	NA
HEATING	Standard Rating Conditions (Low Temperature Steady State Heating)	70.0 [21.1]	60.0 [15.6] (max)	17.0 [-8.3]	15.0 [-9.4]	NA	NA	NA	NA
HEATING	Maximum Operating Conditions	80.0 [26.7]	NA	75.0 [23.9]	65.0 [18.3]	NA	NA	NA	NA

NOTES:
1 The wet-bulb temperature condition is not required when testing air cooled condensers which do not evaporate condensate except for units with optional outdoor cooling coil.
2 Water flow rate as determined from Standard Rating Conditions Test.
3 Cooling rating and operating tests are not required for heating only heat pumps.
4 Make-up water temperature shall be 90.0°F [32.0°C].
5 The ratings for water-cooled outdoor sections in this table apply only to air conditioning-only systems.

Source: AHRI 1230-2010 Performance Rating of Variable Refrigerant Flow (VRF) Multi-Split Air-Conditioning and Heat Pump Equipment

Table A4-2. Water-cooled IPLV (2010 version) Part-Load Rating Conditions

Conditions	°C
Air entering indoor-side Dry-Bulb Wet-Bulb	 27 19
Water-cooled condenser Entering water temperature Water flow rate	100% load: 30, 75% load: 26, 50% load: 23, 25% load: 19 Full load flow

Source: GB/T 17758-2010 Unitary Air Conditioner

Table A4-3. IEER Part-Load Rating Conditions

CONDITIONS	°F	°C
Indoor Air		
Return Air Dry-Bulb Temperature	80.0	26.7
Return Air Wet-Bulb Temperature	67.0	19.4
Indoor Airflow Rate	Note 1	Note 1
Condenser (Air Cooled)		
Entering Dry-Bulb Temperature Outside Air Temperature (OAT)	For % Load > 44.4%, OAT = 0.54 · % Load + 41 For % Load ≤ 44.4%, OAT = 65.0	For % Load > 44.4%, OAT = 0.30 · % Load + 5.0 For % Load ≤ 44.4%, OAT = 18.3
Condenser Airflow Rate (cfm)	Note 2	Note 2
Condenser (Water Cooled)		
Condenser Entering Water Temperature (EWT)	For % Load > 34.8%, EWT = 0.460 · % LOAD + 39 For % Load ≤ 34.8%, EWT = 55.0	For % Load > 34.8% , EWT = 0.256 · % LOAD + 3.8 For % Load ≤ 34.8%, EWT = 12.8
Condenser Water Flow Rate (gpm)	full load flow	full load flow
Condenser (Evaporatively Cooled)		
Entering Wet-Bulb Temperature (EWB)	For % Load > 36.6%, EWB = 0.35 · % Load + 40 For % Load ≤ 36.6%, EWB = 52.8	For % Load > 36.6%, EWB = 0.19 · % Load + 4.4 For % Load ≤36.6%, EWB = 11.6

Source: AHRI 1230-2010 Performance Rating of Variable Refrigerant Flow (VRF) Multi-Split Air-Conditioning and Heat Pump Equipment

The seasonal energy efficiency ratio (SEER) is calculated by summation of cooling load over power input for each outdoor temperature, as cooling seasonal total load (CSTL) / cooling seasonal energy consumption (CSEC), $\sum(cooling\ load \times hours)/\sum(power\ input \times hours)$, in an outdoor temperature range, varying by region.

The heating seasonal performance factor (HSPF) is calculated by summation of heating load over power input for each outdoor temperature as heating seasonal total load (HSTL) / heating seasonal energy consumption (HSEC), $\sum(heating\ load \times hours)/\sum(power\ input \times hours)$, in an outdoor temperature range, varying by region.

The annual performance factor (APF) is as (CSTL+HSTL) / (CSEC+HSEC).

Table A4-4. Temperature Conditions for SEER and HSPF of Variable-Speed Systems

	Cooling			
	Outdoor DB/WB temp. (°C)	Indoor DB/WB temp. (°C)	Outdoor DB/WB temp. (°C)	Indoor DB/WB temp. (°C)
Full capacity (100%)				
Half capacity (50%)	35/24	27/19	7/6	20/15(max)
Minimum capacity (25%)				
Full capacity (100%)				
Half capacity (50%)	29/19	27/19	2/1	20/15(max)
Minimum capacity (25%)				
Full capacity (100%)				
Half capacity (50%)	-	-	-7/-8	20/15(max)
Minimum capacity (25%)				

Note: Performance at the lower temperatures can be calculated by using predetermined equations, for example:
Cooling: Capacity(29°C)=Capacity(35°C)×1.077; Power input(29°C)=Power input(35°C)×0.914
Heating: Capacity(-7°C)=Capacity(7°C)×0.82; Power input(-7°C)=Power input(7°C)×0.64

A5. Detailed Description of the Efficiency Improvement Options Considered in This Study

Asymmetric scroll design: Such structure reduces the leakage of the refrigerant sucking in the compression chamber, and also improves the operating efficiency of the compressor.

Magnet rotor: Such neodymium magnet rotor can efficiently reduce the noise level and control the rotating speed, with the optimized structure.

Torque control: VSDs with torque control systems quickly react to discharge pressure differences, to keep the pressure stable, from high-torque demands at startup to continual use.

180° sine wave control: Such systems provide high precision motor speed control with reducing reactive loss of motor-driven.

Brushless DC motor: These types of motors provides steeples speed regulation and more stable operation, reducing noises as ensuring energy conservation and high efficiency.

Microchannel heat exchangers: Channels with a hydraulic diameter below 1 mm.

Circuit optimization: Optimization of the refrigerant circuitry.

Fin designs: Optimum design structures provide low air resistance and great heat transfer coefficient; also improves frosting efficiency.

Groove patterns: These patterns increase the contact area of the refrigerant and improves the heat transfer efficiency.